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**THE EFFECT OF NUCLEAR RADIATION ON
ELASTOMERIC AND PLASTIC COMPONENTS
AND MATERIALS**

**RADIATION EFFECTS INFORMATION CENTER
Battelle Memorial Institute
Columbus 1, Ohio**

Report on

THE EFFECT OF NUCLEAR RADIATION ON
ELASTOMERIC AND PLASTIC COMPONENTS
AND MATERIALS

by

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to

AIR FORCE SYSTEMS COMMAND
A. NAUTICAL SYSTEMS DIVISION

RADIATION EFFECTS INFORMATION CENTER
Battelle Memorial Institute
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ABSTRACT

This report presents the state of the art of the effects of nuclear radiation on elastomeric and plastic components and materials from 1947 to the present. As such, it supersedes the following REIC documents: Reports 3, 3A, 3-2A, 9, and 13, and Memorandums 1, 3, 8, 15, and 17.

The mechanism of radiation damage and the effects of radiation in various environments are briefly discussed. Data summarizing the radiation-effects information on specific components and on the various types of elastomers and plastics are presented in detail. Areas in which additional work is needed are indicated. Radiation polymerization or vulcanization are included only if the data have a bearing on radiation effects on the finished polymer.

This report is intended to be sufficiently inclusive to make it valuable as a reference guide on the effects which can be anticipated from nuclear radiation on elastomeric and plastic components and materials.

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THE EFFECT OF NUCLEAR RADIATION ON ELASTOMERIC AND PLASTIC COMPONENTS AND MATERIALS

SUMMARY AND CONCLUSIONS

Organic materials are susceptible to damage from all types of nuclear radiation. Consequently, plastics and particularly elastomers, present serious problems in connection with the development of components and systems for nuclear-powered vehicles. In addition to being susceptible to damage by radiation, many of these rubber and plastic materials are adversely affected by environmental conditions, such as extreme temperatures (-100 to +500 F), vacuum, oxidizing atmospheres (ozone), and various types of fuels, lubricants, and hydraulic fluids. Although there are a number of organic materials which have radiation resistance in the range required, they are not useful in the construction of many components and systems because they are lacking in some other needed property. For example, polystyrene has very good radiation resistance but low strength and heat resistance. Therefore, the major problem is to develop materials which will resist radiation and which are also satisfactory in the environments mentioned above. Critical areas are: (1) seals and gaskets, (2) hoses, (3) electrical insulation, (4) transparencies and optical goods, (5) structural units, and (6) adhesives.

At the present time, the emphasis on radiation-effects studies in plastics and elastomers is twofold. First, there is an increase in the dynamic testing of materials in combined environments, such as irradiation at elevated temperatures in air and in fluids. In this connection, data are becoming available on the testing of components and systems under the environmental conditions in which they may be expected to operate. However, results are incomplete because test equipment for varying environmental conditions is difficult to design and it is extremely difficult to determine mechanical and physical properties of samples while they are being irradiated. Secondly, fundamental studies are being directed toward the development of new and improved testing methods and radiation-resistant polymers. The activities in these two areas should result in better materials for applications in nuclear-radiation environments.

Another major problem at present is to determine the effects of radiation and vacuum on the characteristics of polymeric materials. Information currently is limited. Gassing and sublimation may be serious problems in a combined environment such as that found in outer space.

Components

Most of the elastomers have been evaluated as component parts of a system. Tires, insulation, hoses, seals, and gaskets have been exposed to a radiation field. In natural-rubber aircraft tires, other components, such as the cord, were found to be affected more seriously than the rubber. Natural-rubber aircraft tires containing anti-rads have been exposed to 8.4×10^9 ergs g^{-1} (C) and found serviceable for two or more landings after irradiation. Tire cords appear to be the weak spot. Dacron, the most radiation-resistant fiber found for this application, but good adhesion to rubber is

difficult to obtain. Seals and gaskets have been found to have greater resistance when immersed in oil and, as a result, seals of Viton A, silicone, or nitrile rubber are now believed capable of service to an exposure dose of 10^{10} ergs g^{-1} (C), whereas, on the basis of static tests in air, an exposure dose of 10^8 ergs g^{-1} (C) has been considered maximum. On the other hand, elastomers irradiated while under stress have less resistance to radiation than unstressed specimens.

Oil-resistant, nitrile-rubber O-rings are available which can be used to 10^{10} ergs g^{-1} (C). Although this value is somewhat higher than those reported previously, it does not represent an increase in radiation stability, but shows that the O-rings maintain a seal after physical properties have been degraded by irradiation. Viton A and Elastomer 214 O-rings (both copolymers of hexafluoropropylene and vinylidene fluoride) retain rubberlike properties when exposed to 10^{10} ergs g^{-1} (C) in diester fluid at 400 F. However, when these elastomers are irradiated at 400 F, hydrogen fluoride is evolved, creating a corrosion problem. Electrical insulation consisting of glass-mica tape impregnated with silicone resins has satisfactorily withstood an exposure of 10^{14} ergs g^{-1} (C).

Seals, gaskets, sealants, and hoses have been exposed to combined environments in systems and component testing under anticipated environmental conditions and have frequently shown better service characteristics than were anticipated from static data. At elevated temperatures, heat effects appear to be more serious than radiation effects. The lowering of tensile strength with temperature is often greater than that caused by high radiation exposures. In most cases, heat and radiation effects are not additive; for many materials the total effect is less than the sum of the combined environments. In the case of elongation, where the effect of temperature is not great, radiation degradation appears to be the more important factor.

Radiation-damage thresholds of several plastic laminates have been determined at room temperature. Phenolic laminates retained mechanical properties better than such laminates as polyesters, silicones, and epoxies when irradiated. The latter three types of laminates reached threshold-damage levels before an exposure dose of 8.3×10^{11} ergs g^{-1} (C), but phenolic laminates retained useful properties beyond this exposure dose. Also, for some of the laminates, radiation resistance at high temperatures (500 F) has been investigated. Phenolic and epoxy laminates showed exceptionally good radiation stability at temperatures up to 500 F. It was found that flexural strength of phenolic laminates for specimens irradiated at 500 F and 4.2×10^9 ergs g^{-1} (C) was twice as good as that for specimens aged at 500 F without irradiation. Compressive strength of heat-resistant epoxy laminates irradiated at 500 F and 8.3×10^9 ergs g^{-1} (C) was higher than that of specimens aged at 500 F without irradiation. Phenolic laminates have shown no greater decrease in strength due to irradiation when exposed to gamma irradiation at a temperature of 900 F than when exposed to the same temperature with no irradiation.

Present information regarding radiation stability of adhesives is available only for those adhesives developed for structural applications in aircraft and missiles. Irradiation studies on phenolic-epoxy, vinyl-phenolic, nylon-phenolic, epoxy, and nitrile rubber-phenolic types of adhesives, using neutron, electron, and gamma radiation, indicated that each type of radiation caused similar damage at similar dosages. In general, it was found that adhesives developed for high-temperature use, such as the

phenolic-epoxy types, have better resistance to radiation compared with thermoplastic and general-purpose types. Phenolic-epoxy adhesives, such as Shell 422J and Narmcc 25-1 have excellent radiation stability at room temperature. They retain useful strength properties to a radiation-exposure dose of 10^{11} ergs g^{-1} (C). For elevated temperatures (to 500 F), Adhesive 422J appeared to be the best adhesive tested. It retained good shear strength when tested at 500 F after being exposed at room temperature to a radiation dose of 8.1×10^{10} ergs g^{-1} (C). A vinyl-phenolic adhesive on a glass carrier, FM-47, and a modified nylon-phenolic adhesive, Cycleweld C-6, retained good shear strength at 10^{11} ergs g^{-1} (C). Most epoxy and nitrile rubber-phenolic adhesives show good adhesion at room temperature to 5×10^{10} ergs g^{-1} (C). Neoprene-phenolic adhesives appear to be useful to 10^{10} ergs g^{-1} (C). The rubber-phenolic adhesives are generally more flexible than the phenolic-epoxy type, but the bonded areas tend to creep under shear stress.

In general, a filler improves the radiation stability of an adhesive, although in some cases at a sacrifice of the over-all shear strength. The curing agent and reactive diluent used in epoxy adhesives will also influence the radiation stability of the adhesive. Aromatic curing agents generally produce more radiation-resistant compositions than do the aliphatic curing agents.

The maximum variation doses to which various components can be exposed and still retain useful properties are shown graphically in Figure 1.

Elastomers

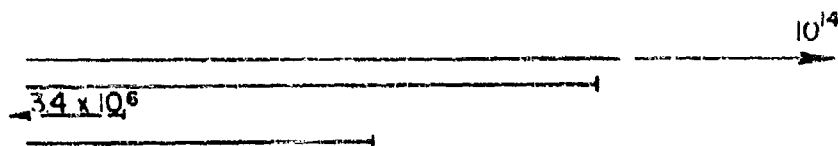
On the basis of current data, the most radiation-resistant elastomers are polyurethanes, adduct rubbers (diene elastomers in which the unsaturation is reduced by treating with an alkyl mercaptan), and natural rubber. The polyurethane elastomers may be used for dynamic applications up to exposure doses in the range of 1.7×10^{11} ergs g^{-1} (C), and for static applications, up to 4.4×10^{11} ergs g^{-1} (C). However, radiation stability may be lower if moisture is present, since polyurethane elastomers are sensitive to water. The adduct rubbers possess some strength and flexibility at an exposure dose of 8.7×10^{10} ergs g^{-1} (C). For dynamic applications they should be satisfactory to an exposure of approximately 1 to 2×10^{10} ergs g^{-1} (C). Natural rubber, although possessing a fair amount of flexibility at 8.7×10^{10} ergs g^{-1} (C), can be considered as having an exposure limit of 4×10^{10} ergs g^{-1} (C) for static operations and 5×10^9 ergs g^{-1} (C) for dynamic operations. Natural rubber and GR-S have life expectancies of about 200 hours when exposed in radiation fields of about 10^7 ergs g^{-1} (C) in the absence of air. In general, most elastomers increase in hardness when irradiated. Butyl and Thiokol rubbers, however, soften and become liquid with high radiation doses. The relative radiation resistances of the various elastomers are shown graphically in Figure 2.

Elastomers irradiated and tested at a slightly elevated temperature (158 F) have illustrated the importance of testing materials at operating temperatures. In general, heat and radiation effects are not additive for elastomers. In most cases, the combined effects were less than the additive effects.

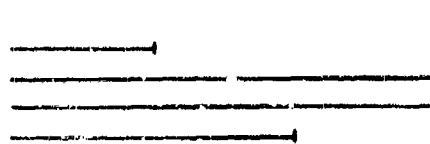
Elastomers generally acquire a high compression set when irradiated at elevated temperatures while they are compressed. On the other hand, if they are irradiated while relaxed, compression set ordinarily is less than the initial value. It is believed

Electric Insulation:

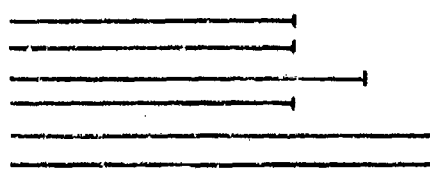
Silicon - glass mica
 Silicone, filled
 Teflon, in air
 Teflon, in fluid

Seals:

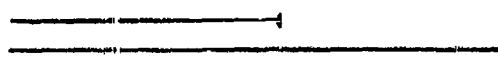
Viton A or Silicone,
 In air
 In oil
 Nitrile rubber
 Neoprene rubber

Sealants:

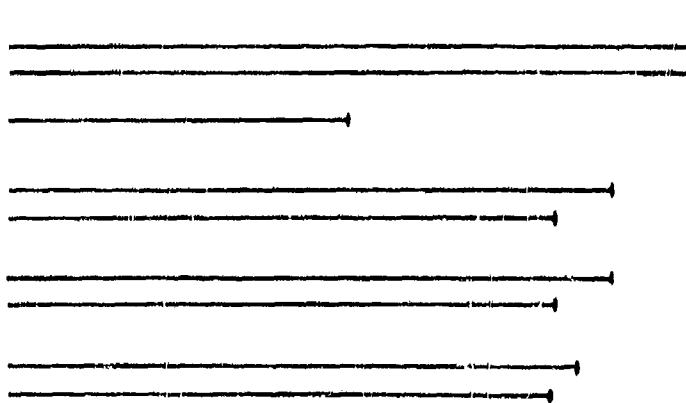
Viton A, in air
 Silicone, in air
 Thiokol, in fuel
 Neoprene, in air
 Nitrile, in air
 Viton B, in air

O-Rings:

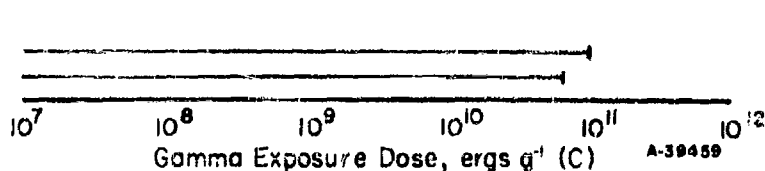
Viton A, in oil
 Natural rubber

Tires, with antiradLaminates:

Phenolic
 Room temperature
 500 F
 Phenolic, irradiated and
 tested at 500 F
 Epoxy
 Room temperature
 500 F
 Silicone
 Room temperature
 500 F
 Polyester
 Room temperature
 500 F

Adhesive:

422J
 Room temperature
 500 F

Gamma Exposure Dose, ergs g⁻¹ (C)

A-39459

FIGURE 1. MAXIMUM RADIATION EXPOSURE OF VARIOUS COMPONENTS
 FOR RETENTION OF USEFUL PROPERTIES

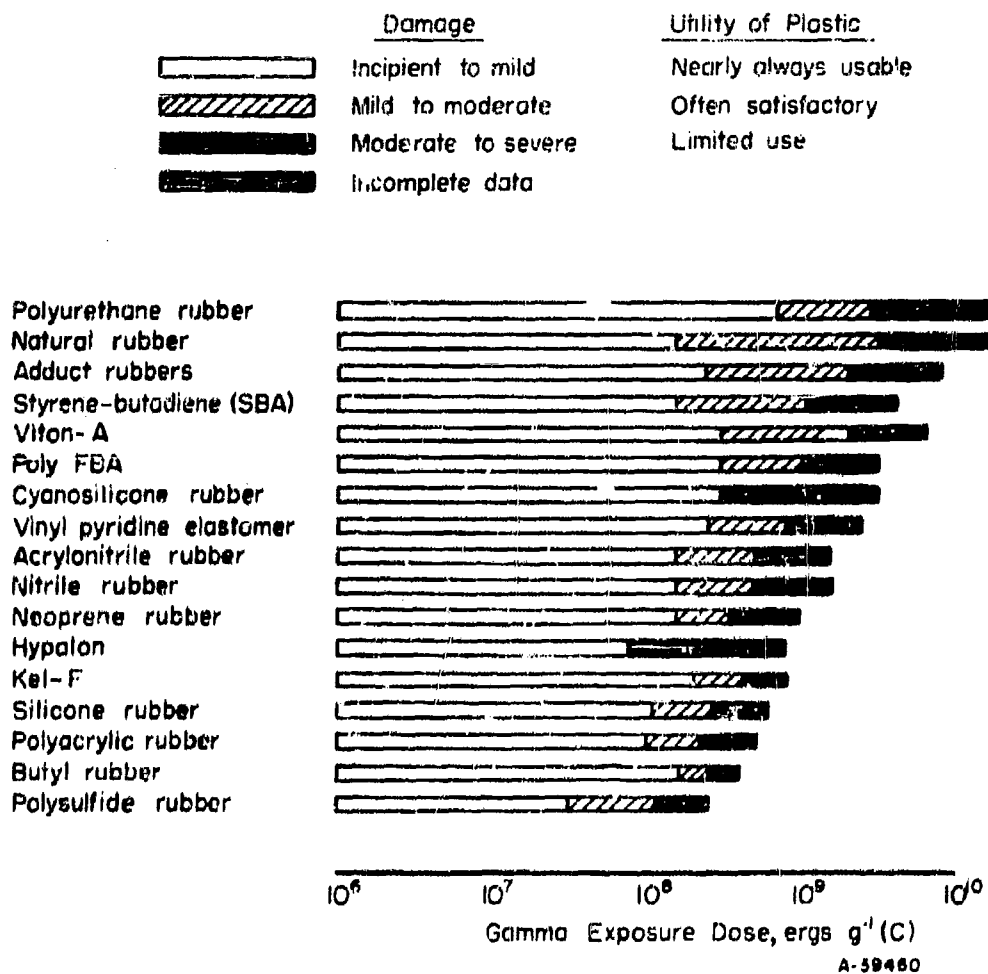


FIGURE 2. RELATIVE RADIATION STABILITY OF ELASTOMERS

that this difference is due to the fact that crosslinking of an elastomer in the compressed state will tend to set the rubber permanently in the strained condition, whereas, when the rubber is irradiated in an unstressed condition, the crosslinking results in a more rigid structure which tends to resist subsequent compression set.

The presently available rubbers for use above 300 F do not have good radiation-resistant properties. Silicones and fluorine-based polymers, the best temperature-resistant rubbers, are below average in radiation resistance. Nitrile rubber, and to a lesser extent, neoprene rubbers, are being used for radiation applications at temperatures below 300 F.

It has been found that the radiation resistance of an elastomer is dependent on the composition of the compound, i. e., type of curing agents, antioxidants, fillers, and other additives utilized in their preparation, and to the processing and curing conditions. Filler-loaded elastomers are more resistant to radiation than the pure gum stock; carbon black appears to be the best filler for improving a compound's radiation resistance. Curing conditions are also important; indications are that it is best to have the rubber compound slightly undercured.

Although these factors influence the radiation stability of elastomers, improvement by a factor of 2 to 10 can be realized only through the use of certain protective agents, such as amines and phenols, which have been given the name of antirads. These materials often have antioxidant properties. The best material found thus far is N, N'-cyclohexylphenyl-p-phenylenediamine. At a radiation dose of 10^6 ergs g^{-1} (C), it has increased the life of natural rubber more than tenfold. Antirads are, however, specific in that some are more effective with one type of polymer than with another. There is still a need for antirads that would be effective with Viton A elastomer. Tests in which over 100 materials were evaluated as potential antirads showed that the best results are obtained if the antirad is utilized in combination with the commonly used antioxidant, phenyl beta naphthylamine.

Plastics

In general, plastics are equal or superior to elastomers in radiation resistance, but are inferior in their resistance to metals and ceramics. Among the plastics, the rigid types are the more radiation-resistant materials.

At present, the materials which will operate satisfactorily in the range of 10^{10} to 10^{11} ergs g^{-1} (C) are glass-fiber- and asbestos-filled phenolics, certain epoxy systems, polyurethane, polystyrene, mineral-filled polyester, mineral-filled silicones, furane-type resins, and polyvinyl carbazole. The next best materials, satisfactory in the range of 10^9 to 10^{10} ergs g^{-1} (C), include polyethylene, melamine-, urea-, and aniline-formaldehyde resins, unfilled phenolic resins, and silicone resins. Of the latter, urea-formaldehyde with cellulose pulp as filler is about average in radiation stability.

Methyl methacrylate and unfilled polyesters have relatively poor radiation stability as compared with other plastics. However, compared with elastomers, they are about equal to SBR, one of the more radiation-resistant synthetic rubbers. Materials having poor radiation stability include the celluloses, polyamides, and Teflon.

The relative radiation resistances of the thermosetting and thermoplastic resins are shown graphically in Figures 3 and 4, respectively.

Difficulties are experienced with fluorine-containing materials, such as Teflon, Kel-F, or PVC in a radiation environment, due to degradation of physical properties and to the liberation of halogen or halogen acid which have corrosive effects on adjacent components. This occurs at approximately 10^6 ergs g^{-1} (C) for Teflon, 10^8 ergs g^{-1} (C) for Kel-F, and 10^9 ergs g^{-1} (C) for PVC. Gassing of most plastics is another problem in enclosed or poorly ventilated systems.

Several methods of improving the radiation resistance of plastics have been investigated. These are the addition of mineral fillers, ceramic fibers, and organic additives. Mineral fillers and ceramic fibers improve the radiation resistance of most plastics. The improvement may be the result of the formation of more rigid structures or may be due to the absorption of a portion of the radiation energy by the filler. Little success has been achieved with organic scintillators except with 2, 5-diphenyloxazole, which was found to improve the radiation resistance of an epoxy adhesive by a factor of four.

Recommendations

Additional information on radiation resistance of polymers is needed in the following areas:

- (1) More data are needed on service life of components, such as seals, sealants, laminates, and adhesives under high vacuum, heat, and radiation.
- (2) The effects of radiation at high temperatures and extremely low (cryogenic) temperatures. The need for elastomers and plastics for use at these temperatures becomes more acute with the development of space vehicles. Little is known of how materials will function under radiation at high and extremely low temperatures. Some progress has been made in the design of such polymers, but none are, as yet, available for use above 750 F.
- (3) Data are needed on the combined effects of radiation and vacuum on polymeric materials.
- (4) Methods for predicting life of polymers in a radiation field are needed.
- (5) Additional information on the mechanism of radiation damage on polymers that will be helpful in designing radiation- and heat-resistant polymeric systems. To develop such systems, greater emphasis should be placed on more stable molecular structures or structures having the ability to convert absorbed radiant energy to other forms of energy which may be dissipated with little or no damage to the base material. At present, research is being directed

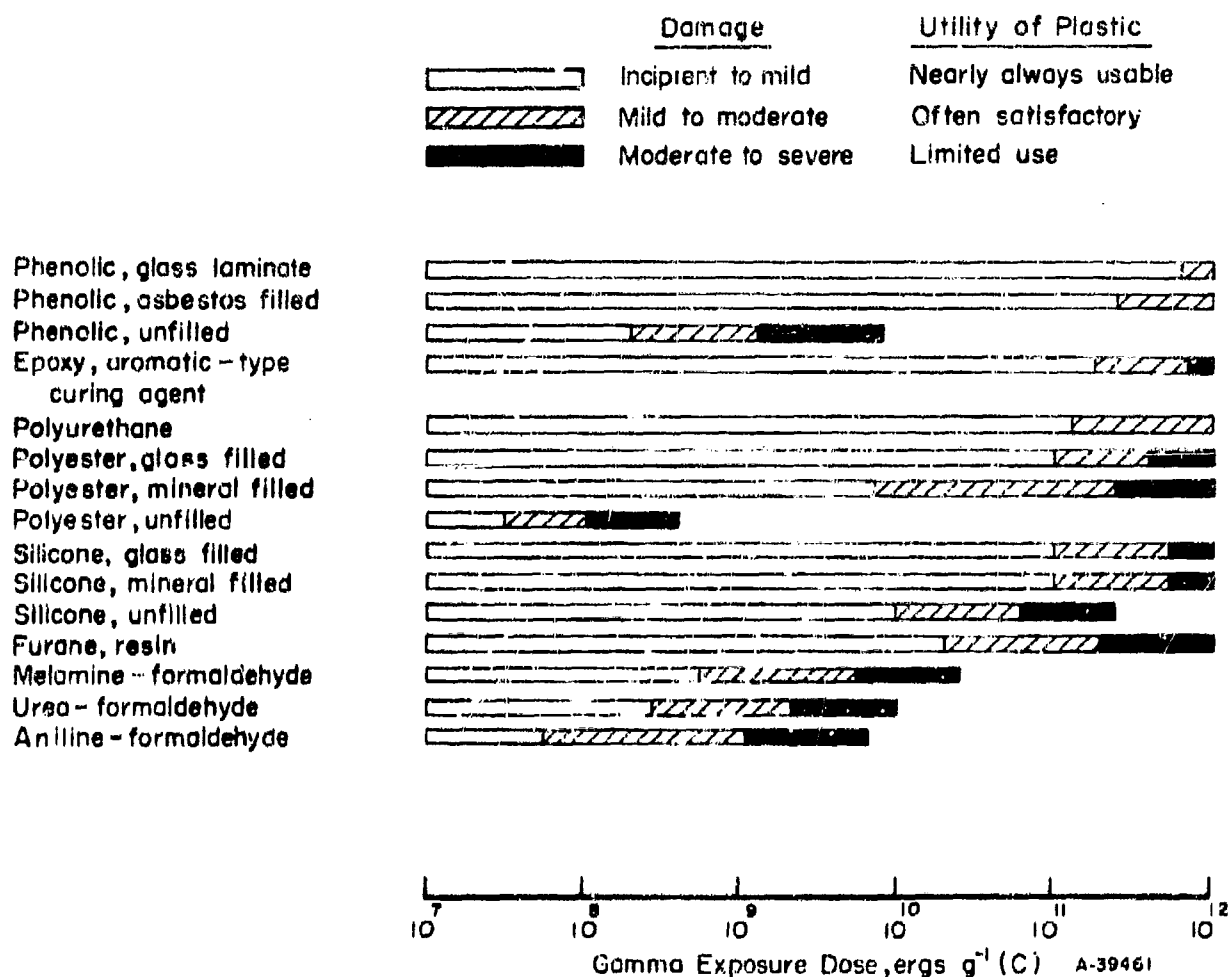


FIGURE 3. RELATIVE RADIATION STABILITY OF THERMOSETTING RESINS

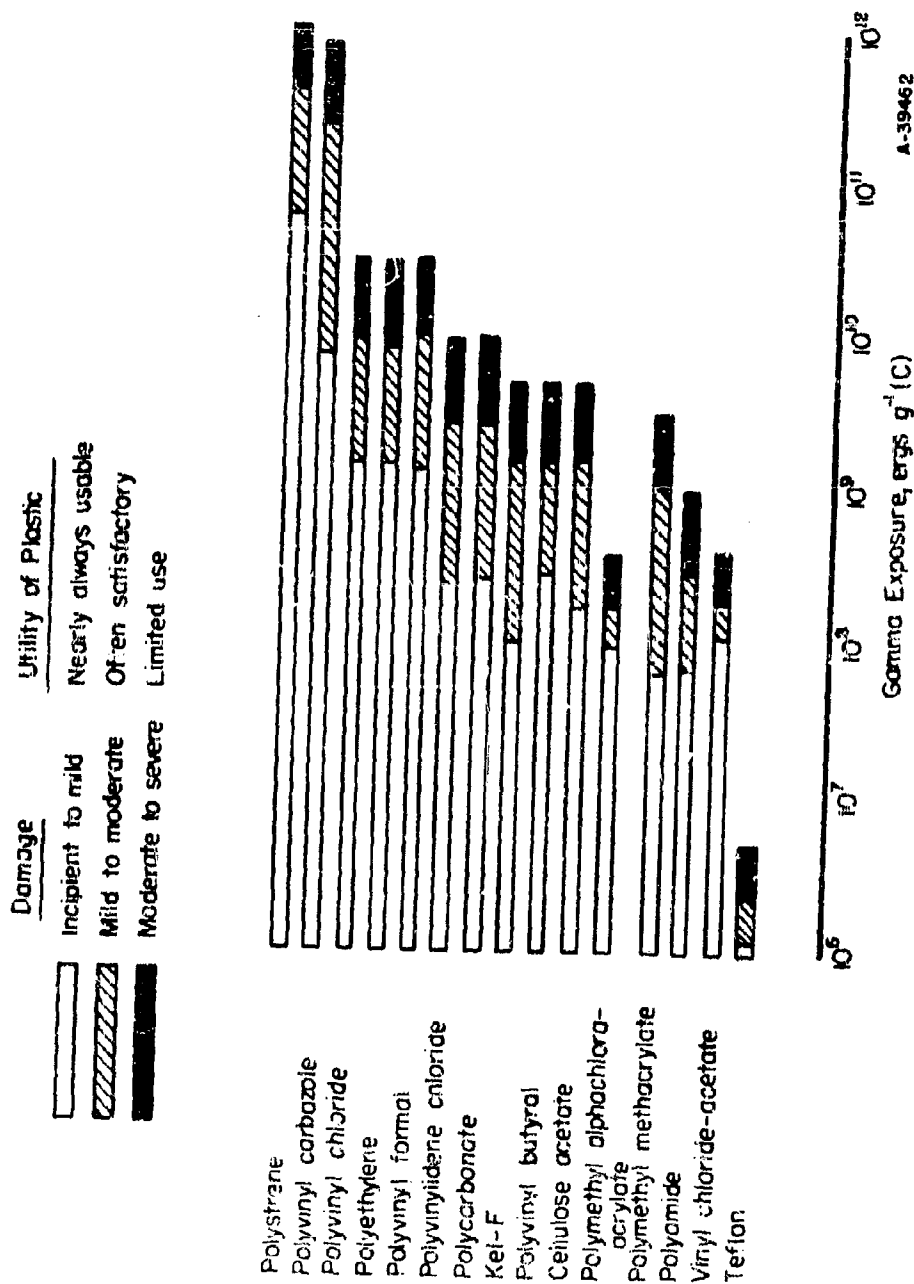


FIGURE 4. RELATIVE RADIATION RESISTANCE OF THERMOPLASTIC RESINS

toward resonating structures and the inclusion of radiation-resistant organic groups and metals in the polymer chain. These studies should be continued at a high rate of effort, since it appears that structures that are stable to heat may also be stable to radiation.

INTRODUCTION

This report presents the state of the art on the effects of nuclear radiation on elastomeric and plastic materials. It is a compilation of the data published in past REIC reports and, therefore, supersedes the following REIC documents: Reports 3, 3A, 3-2A, 9, and 13, and Memorandums 1, 3, 8, 15, and 17. Included are the data obtained during the period April 30, 1960, through April 30, 1961. Thus, this report summarizes the available information on radiation effects on polymeric components and materials.

Most of the earlier available data on radiation effects on rubber and plastic materials represented studies on small, thin specimens subjected to a variety of radiation dosages and the physical properties of the specimens after exposure. Only a relatively small number of studies took into consideration exposure rate and sample thickness. Also, only a few, limited studies involved (1) operational data and (2) combined effects of radiation and other conditions such as temperature and atmosphere. Later information indicated that operational data did not always correlate with experimental results. In some cases, longer operation was experienced than that predicted from the experimental data on polymers irradiated in air under static conditions.

Data for fabricated parts tested under dynamic test conditions or under various environments, such as exposure at higher temperatures, exposure in various thicknesses in air, or exposure while immersed in oil or fuel, have become available. Included are the radiation stability of end items, such as tires, O-rings, and plastic laminates under various environmental conditions. Components and systems have been tested under anticipated environmental conditions. These studies give additional information on the radiation stability of rubber and plastic parts.

In addition to the testing of components and systems, a greater emphasis on fundamental work is noted in the reports published during the past few years. Although this type of research is necessary for developing elastomers and plastics having improved radiation and temperature stability, it will probably be some time before such new and improved materials will be available for engineering applications. A section indicating the fundamental work in progress has been included in this report.

Radiation-effects information is available on a variety of rubber and plastic materials. This information is at times conflicting because workers have not used identical compositions and equivalent radiation conditions in their experimental studies. However, it has been reported that, in general, elastomers are not as resistant as most plastics. Elastomers are resistant up to doses of 10^8 ergs g^{-1} (C), while most plastics are not affected until 10^8 to 10^9 ergs g^{-1} (C), and some are not affected by doses of 10^{10} ergs g^{-1} (C). The range of radiation doses at which various elastomers are changed by 25 per cent is approximately 10^8 to 10^9 ergs g^{-1} (C). For plastics, this range varies from approximately 10^6 to 10^{11} ergs g^{-1} (C).

Tables 1, 2, and 3 show the effect of radiation on some of the more commonly used elastomers and plastics. These tables list radiation doses at which (1) threshold damage occurs, i. e., at least one physical property begins to change; and (2) 25 per cent damage is accrued, i. e., at least one physical property is changed by 25 per cent. Any deviation from the original value, either an increase or a decrease, is considered damage. It must be recognized that all the physical properties of rubbers and plastics do not change to the same degree and, consequently, the relative order of stability may differ from those given in the tables, if the comparison is made on the average change of

TABLE 1. RELATIVE RADIATION RESISTANCE OF ELASTOMERS

Material	Radiation Dosage Required for Threshold Damage, ergs g ⁻¹ (C)	Radiation Dosage Required for 25 Per Cent Damage, ergs g ⁻¹ (C)
Polyurethane rubber	8.7×10^8	4.3×10^9
Natural rubber	2×10^8	5.0×10^9
Adduct rubbers	4.2×10^8	3.0×10^9
Styrene-butadiene, SBR(GR-S)	2×10^8	1.3×10^9
Viton A	5×10^8	3.0×10^9
Poly FBA	5×10^8	1×10^9
Cyanosilicone rubber	--	1×10^9
Vinyl Pyridine elastomers	4×10^8	9×10^8
Acrylonitrile rubber	2×10^8	7×10^8
Nitrile rubber	2×10^8	7×10^8
Neoprene rubber	2×10^8	5.5×10^8
Hypalon (chlorosulfonated polyethylene)	--	4×10^8
Kel-F	3×10^8	6×10^8
Silicone rubber	1.3×10^8	4.2×10^8
Polyacrylic rubber	1×10^8	3.3×10^8
Butyl rubber	2×10^8	4×10^8
Polysulfide rubber (Thiokol)	5×10^7	1.5×10^8

TABLE 2. RELATIVE RADIATION RESISTANCE OF THERMOSETTING RESINS

Material	Radiation Dosage Required for Threshold Damage, $\text{ergs g}^{-1} (\text{C})$	Radiation Dosage Required for 25 Per Cent Damage, $\text{ergs g}^{-1} (\text{C})$	Remarks
Phenolics			
Laminated, glass fiber	$>8.3 \times 10^{11}$	--	Radiation at high temperature improves properties
Asbestos filled	3.9×10^{11}	$>3.9 \times 10^{11}$	
Unfilled	2.7×10^8	1.1×10^9	
Epoxy	2.5×10^{11}	8.3×10^{11}	Resistance dependent on curing system
Isocyanate, foam sandwich	$>1 \times 10^{11}$	--	
Polyester			
Laminated, glass fiber	1×10^{11}	--	
Mineral filled	8.7×10^9	3.9×10^{11}	
Unfilled	5×10^7	1.2×10^9	
Mylar film	4.4×10^8	8.7×10^9	
Allyl diglycol carbonate	1.6×10^8	9.0×10^9	
Silicones			
Laminated, glass fiber	1×10^{11}	--	
Mineral filled	1×10^{11}	--	
Unfilled	1×10^{10}	--	
Ethane Resin	3.3×10^{10}	3.3×10^{11}	Asbestos and carbon-black filled
Amino Resins			
Melamine-formaldehyde	7.4×10^8	7.3×10^9	
Urea-formaldehyde	4.6×10^8	3.3×10^9	
Aniline-formaldehyde	7.4×10^7	1.4×10^9	Data for impact strength only; other properties are good to $10^{10} \text{ ergs g}^{-1} (\text{C})$

TABLE 3. RELATIVE RADIATION RESISTANCE OF THERMOPLASTIC RESINS

Material	Radiation Dosage Required for Threshold Damage, ergs g ⁻¹ (C)	Radiation Dosage Required for 25 Per Cent Damage, ergs g ⁻¹ (C)
Polystyrene	8×10^{10}	$>4 \times 10^{11}$
Polyvinyl carbazole	$\sim 8.8 \times 10^9$	$\sim 4.4 \times 10^{11}$
Polyvinyl chloride	1.9×10^9	1.1×10^{10}
Polyethylene	1.9×10^9	9.3×10^9
Polyvinyl formal	1.6×10^9	1.2×10^{10}
Polyvinylidene chloride (Saran)	4.1×10^8	4.5×10^9
Polycarbonate	4.3×10^8	4.3×10^9
Kel-F	1.3×10^8	2×10^9
Polyvinyl butyral	4.7×10^8	1.9×10^9
Cellulose acetate	2.7×10^8	1.9×10^9
Polymethyl alpha-chloroacrylate	1.0×10^8	2.2×10^8
Polymethyl methacrylate	8.2×10^7	1.1×10^9
Polyamide (Nylon 6,6 or Nylon -6)	8.6×10^7	4.7×10^8
Vinyl chloride-acetate	1.4×10^8	2.5×10^8
Teflon	1.7×10^6	3.7×10^6
Acetal (polyformaldehyde)	Very poor resistance at 4.4×10^8	
Polypropylene	No specific data; but is much inferior to polyethylene	

the over-all properties or the change of a specific property. In general, however, tables representing the average over-all change of the materials would be similar to those given.

In general, conclusions and necessary supporting data are presented in the text. More complete data can be found in the appendixes.

THEORETICAL CONSIDERATIONS IN IRRADIATION OF ORGANIC MATERIALS

Atomic fission produces many kinds of radiation or nuclear particles, but only two of these, neutrons and gamma photons, are able to penetrate more than a few centimeters of solid material. Because the shielding around the reactor and the fissioning fuel will absorb all but these two types, aircraft engineers are concerned primarily with neutrons and gamma photons. These photons and neutrons, on passing through metals, will cause ionization, electronic excitation, atomic displacement, lattice disturbances, and transmutation. (1)

Organic materials, on the other hand, consist primarily of carbon and hydrogen bound together by chemical bonds that are relatively easy to break with the addition of energy. Both gamma rays and neutrons can cause molecular changes which will greatly affect the properties of the material. Fast neutrons can react in several ways. Incident fast neutrons give up approximately one-half of their energy per collision to the target hydrogen atoms. These recoiling atoms can become ionized, and the slow neutrons resulting from the collisions can react with nuclei, releasing strong gamma rays. The gamma rays from these capture reactions may cause the formation of new radical groups or free radicals and ionization. (2)

Organic materials are, as a result, inferior to metals with respect to radiation stability (see Figure 5). Crystalline materials, metals, and ceramics are relatively insensitive as a class to nuclear radiation. Noncrystalline organic materials, on the other hand, are severely damaged by radiation doses thousands of times lower than that necessary to affect metals and ceramics detectably.

Factors affecting radiation damage include the type, amount, and rate of radiation, the composition of the organic material, and the volume of the material subjected to radiation. Damage which occurs is proportional to the amount of radiation absorbed, and one of the problems has been to determine accurately the amount of radiation to which a material is subjected and which it absorbs.

It is extremely difficult to compare radiation data from tests obtained under various radiation sources. Because of the differences in the over-all radiation spectrum of a graphite-moderated and a water-moderated reactor, or a cobalt-60 and a spent-fuel gamma source, the damage that radiation from these sources causes to various materials will differ, although the total absorbed energy may be the same in each case. Therefore, in presenting the experimental work, it is necessary to specify the radiation spectrum, as well as the energy absorbed, when making a comparison of damage to various materials irradiated under different sources. This is particularly true with crystalline materials. With organic materials, these differences in spectra are not so important because, for the range of energies of most interest and for most organic

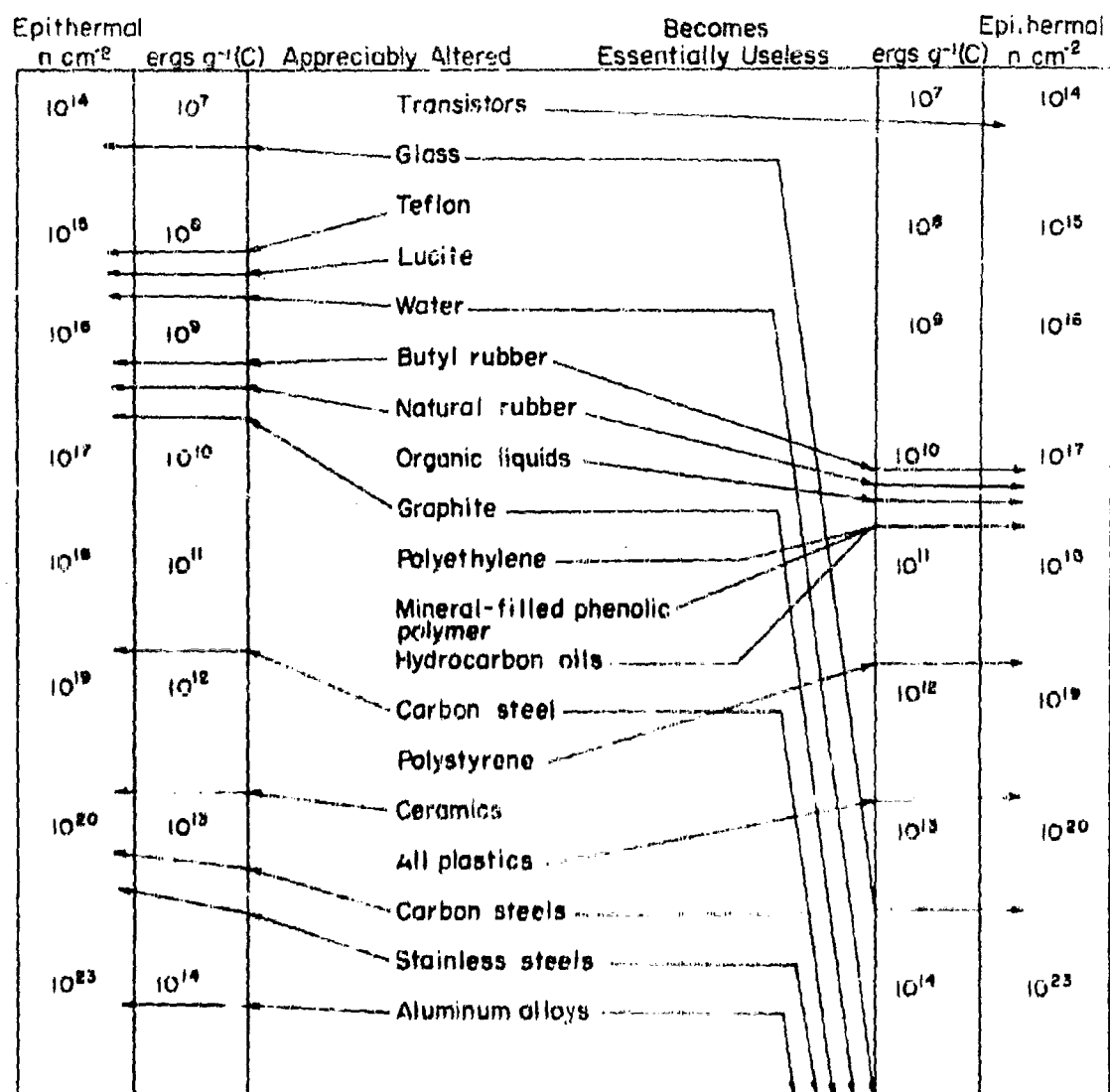


FIGURE 5. RADIATION RESISTANCE OF VARIOUS TYPES OF MATERIALS

Note: Source is G. R. Hennig, "Moderators, Shielding and Auxiliary Equipment", talk given at the colloquium on The Effects of Radiation on Materials, at Johns Hopkins University, March, 1957.

compounds, it can be assumed that the total energy absorbed determines the amount of damage, whether this energy comes from gammas, neutrons, or both.

GENERAL EFFECTS OF RADIATION ON POLYMERIC MATERIALS

Elastomers and plastics are primarily organic materials which consist of carbon and hydrogen atoms bound together by covalent bonds that are easily disrupted by the addition of radiation energy. In this respect they differ from metals and ceramics which are primarily crystalline, do not contain covalent bonds, and are not readily affected by radiation. Consequently, elastomers and plastics are inferior to metals and ceramics with respect to radiation resistance.

Polymeric compounds exhibit several types of changes on irradiation. (3) Most changes depend only on total dose. Some are dose-rate dependent because of the influence of dose rate on free-radical concentration. Some changes are of high enough order to serve as measures of radiation dose.

Radiation-induced changes have their origin in the rupture of covalent bonds in organic molecules. Effects are small in simple organic compounds, but are much more pronounced in polymers. Among radiation-induced changes in rubber and plastics are those in appearance, chemical state, physical state, and mechanical properties. Appearance changes with temporary and permanent color effects and bubbling. Chemical changes include double-bond formation, dehydrochlorination, crosslinking, oxidative degradation, polymerization, depolymerization and gas evolution. Physical changes include effects on viscosity, solubility, conductivity, free-radical spectra, fluorescence, and crystallinity. Changes in crystallinity are indicated by measurements of density, heat of fusion, X-ray diffraction, and other properties. Mechanical properties that change are tensile strength, elastic modulus, hardness, elongation, flexibility, etc.

Fast-neutron and gamma radiation emitted from a nuclear reactor produce various chemical reactions in plastics and rubbers; these, in turn, change the physical properties of the materials. (4) The new chemical bonds formed by radiation are irreversible and cannot be removed by post-irradiation heating.

Several reactions occur concurrently with irradiation, but the dominating reactions and the rates at which they proceed depend upon the chemical structure of the material. For many plastics and rubbers, the effect is essentially a curing process characterized by an increase in hardness, a decrease in solubility, and sometimes, initially, by an increase in strength. A moderate amount of radiation may be beneficial to these materials, but ultimately, in a radiation field, they lose tensile, shear, and impact strengths and elasticity, and finally become brittle. Gas is often evolved during irradiation. Other types are degraded by radiation; they soften and become sticky or eventually disintegrate into a powdery substance. Irradiation also makes organic materials more susceptible to oxidation.

Materials in which the curing effect predominates (crosslinking) include polyethylene, polystyrene, silicone, natural rubber, neoprene, GR-S rubber, and Buna-N rubber. Teflon, Kel-F, Lucite, cellulose plastics, butyl rubber, and Thiokol are predominantly affected by chain scission and, consequently, softening of the material.

Certain materials, called antirads, are known to inhibit radiation damage. These include aromatic structures, certain antioxidants, and mineral fillers. Research is being carried out to find the most effective inhibitors.

Inorganic fillers usually increase radiation resistance. Laminates of glass cloth have more structural stability than the resins alone, but fillers such as cloth and paper reduce radiation resistance.

Sisman and Bopp⁽⁵⁾ determined the effect of polymeric structure on the radiation stability of plastics and have ranked the structural groups in the order of their stability (see Figure 6). From this it can be seen that the benzene group attached to the main chain but not present as part of the chain, provides the greatest radiation stability to the polymers, while the presence of quaternary carbon atoms leads to radiation instability.

All the properties of a polymer are not affected to the same degree by radiation. Therefore, in determining which rubber or plastic is best for a particular application, it is necessary to consider the effect of radiation in two ways. First, the over-all radiation stability of the material must be taken into account, and second, the effect of radiation on those properties which are important for the desired application must be considered. For example, two elastomers may have good over-all radiation stability, but with one, the tensile strength fails first under irradiation, while with the other, the compressive strength is the property which deteriorates most rapidly. The first rubber could be used most advantageously for applications where compressive strength is one of the important requirements, such as in gaskets or seals. The latter rubber could serve best for applications where retention of tensile strength is most important.

At present, no commercially available, new or improved radiation-resistant polymers are in sight. However, as more information on the structural factors affecting radiation resistance is obtained, new polymers will be synthesized to take advantage of this knowledge.

It is believed that polystyrene has excellent radiation resistance because the benzene ring absorbs energy due to resonance within the ring structure. Other resonating structures, such as ferrocene, are being examined to determine which structures may be used to reduce the effect of radiation. No published information is available on this work at the present time.

Certain organic groups are known to be more stable than others, and the following general rules lay the ground work for formulations of radiation-resistant species. (6)

- (1) Aromatics are more stable than aliphatics because of the resonance energy and greater bond strength of the aromatics. The greater the resonance energy, the greater the stability. In order of decreasing stability are anthracene, naphthalene, benzene, and aliphatics.
- (2) Substituted aromatics are more resistant than unsubstituted aromatics. A side group acts as a point of entry for energy to enter the ring and be dissipated. In order of decreasing stability are ortho, para, and meta substituted groups.
- (3) Basic compounds are more stable than acid compounds because the bonds of the COOH group are relatively weak.

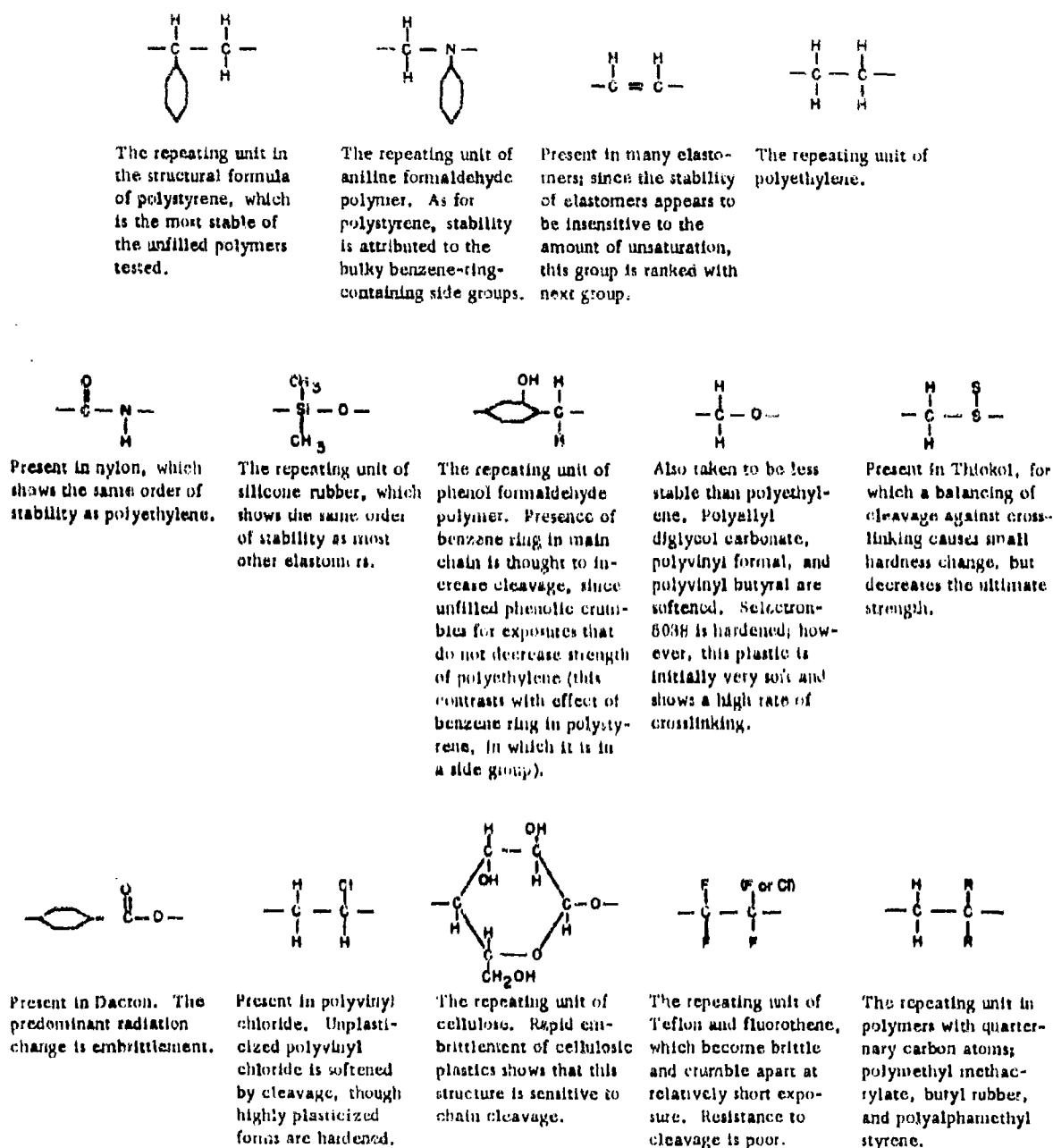


FIGURE 6. POLYMER GROUPS RANKED IN ORDER OF STABILITY AGAINST CLEAVAGE⁽⁵⁾

- (4) In order of decreasing stability are alkanes, ethers, alcohols, esters, and ketones. These relations may be due to relative electronegativity and relative bond strengths.
- (5) Saturated aliphatic structures are more stable than unsaturated aliphatic structures. Compounds with terminal unsaturation are less stable than compounds with interior unsaturation.
- (6) Small molecules are more stable than large molecules. Smaller volume per molecule means less absorption per molecule.
- (7) Nonbranched chains are more stable than branched chains. There is a greater possibility of crosslinking in branched chains.
- (8) Trans-isomers are more stable than cis-isomers and equatorial groups are more stable than axial groups. Steric hindrance of axial groups promotes instability.

ESTIMATE OF LIFE EXPECTANCY OF POLYMERIC MATERIALS

At present, there are only limited data available which correlate laboratory tests and service life of a polymeric material at different radiation doses. However, on the basis of the rate of change of the polymer on exposure to radiation, it is possible to estimate life expectancy to some degree.

Using an assumed radiation field in which the materials would absorb energy at a rate of 10^7 ergs $\text{g}^{-1} \text{hr}^{-1}$, the life expectancy of several elastomers was calculated. Tables 4 and 5 indicate the number of hours at which elastomers and plastics are damaged to threshold, 25 per cent, and 50 per cent values. It was obtained by dividing the doses necessary for these degrees of damage by 10^7 ergs $\text{g}^{-1} \text{hr}^{-1}$ (C). The tables are only indicative of the relative service life of materials and cannot be interpreted as actual service life.

There are a great many variables affecting the service life of a material while under irradiation. The cure, filler, and other compounding ingredients will have some effect, and the environment to which the material is subjected will also determine, to some extent, its service life. Therefore, tests under actual service-life conditions are necessary before an estimate of life expectancy can be made with any degree of accuracy.

THE EFFECTS OF RADIATION IN COMBINED ENVIRONMENTS

The majority of the work to date on the effects of radiation on polymeric compounds has been under normal environmental conditions, i. e., in air and at ambient temperature. However, there is a steadily increasing number of reports on the effects of radiation on compositions (1) at elevated temperature, (2) in vacuum, (3) on immersion in liquids or gases, and (4) in combinations of these environments. These data are summarized below.

TABLE 4. HOURS TO PRODUCE DAMAGE TO ELASTOMERS IN A FIELD IN WHICH MATERIALS ABSORB 10^7 ERGS G^{-1} HR $^{-1}(G)$

Property and Original Value	Absorbed Total Dose to Produce Damage, ergs G^{-1} (C)			Hours to Produce Indicated Damage to Elastomers		
	Threshold Damage	25 Per Cent Damage	50 Per Cent Damage	Threshold Damage	25 Per Cent Damage	50 Per Cent Damage
Natural Rubber						
Tensile strength (2,600 psi)	$2.2 \times 10^9(b)$	1.4×10^{10}	3×10^{10}	220	1400	3000
Elongation (420 per cent)	6.8×10^8	4.5×10^9	1.2×10^{10}	68	450	1200
Set at break (12 per cent)	4.5×10^8	2.4×10^9	6.8×10^9	45	230	680
Compression set (13 per cent)	1.8×10^8	5×10^9	10^{10}	18	500	1000
Strain at 400 lb/in. ² (30 per cent)	9.1×10^8	9.1×10^9	3×10^{10}	91	910	3000
Shore hardness (C)	8.4×10^8 (H = 60)	2.2×10^9 (H = 65)	4.5×10^9 (H = 70)	84	220	450
Butyl Rubber (GR-150)						
Tensile strength (1,100 psi)	6.4×10^8	2.1×10^9	3.8×10^9	64	210	380
Elongation (525 per cent)	6.4×10^8 or 1	5×10^9	--	64	500	--
Set at break (35 per cent)	2.2×10^8	6.4×10^8	1.5×10^9	22	64	150
Compression set (72 per cent)	1.8×10^8	3.6×10^8	5.9×10^8	18	36	59
Strain at 400 lb/in. ² (31 per cent)	9.1×10^8	2.2×10^9	3.2×10^9	91	220	320
Shore hardness	2.1×10^9 (H = 66)	3.2×10^9 (H = 61)	3.9×10^9 (H = 56)	210	390	350
Nitrile Rubber (Hycar GR-15)						
Tensile strength (1,900 psi)	2.7×10^9	1.5×10^{10}	2.9×10^{10} (40%)	270	1500	5300
Elongation (250 per cent)	2.1×10^8	1.5×10^9	5.8×10^9	21	150	580
Set at break (3 per cent)	--	--	7.4×10^8	--	--	74
Compression set (9.5 per cent)	1.4×10^8	6.4×10^8	1.5×10^9	14	64	150
Strain at 400 lb/in. ² (25 per cent)	3.2×10^8	2.7×10^9	2.4×10^9	320	270	730
Shore hardness	7×10^7 (H = 72)	2×10^9 (H = 77)	5×10^9 (H = 82)	7	200	500
Polyacrylic Rubber (Hycar PA-21)						
Tensile strength (2,000 psi)	4.1×10^8	5.5×10^9	1.4×10^{10}	41	550	1300
Elongation (236 per cent)	2.9×10^8	1.6×10^9	3.3×10^9	29	160	330
Set at break (10 per cent)	9.1×10^7	3×10^8	6.7×10^8	9.1	30	67
Compression set (5 per cent)	1.8×10^8	1.1×10^9	6.4×10^9	18	110	180
Strain at 400 lb/in. ² (35 per cent)	4.5×10^8	3.2×10^9	2.1×10^{10}	45	320	2100
Shore hardness	4.7×10^7 (H = 62)	3.9×10^8 (H = 67)	1.2×10^{10} (H = 72)	4.7	30	1200

TABLE 4. (Continued)

Property and Original Value	Absorbed Total Dose to Produce Damage, ergs g^{-1} (C)			Hours to Produce Indicated Damage to Elastomers		
	Threshold Damage	25 Per Cent Damage	50 Per Cent Damage	Threshold Damage	25 Per Cent Damage	50 Per Cent Damage
Polychloroprene Rubber (Neoprene W)						
Tensile strength (2,900 psi)	10^9	$6.6 \times 10^9 \downarrow$	$1.6 \times 10^{10} \downarrow$	100	660	1600
Elongation (450 per cent)	$4.1 \times 10^8 \uparrow$	$1.8 \times 10^9 \downarrow$	$4.1 \times 10^9 \downarrow$	41	180	410
Set at break (6 per cent)	$1.6 \times 10^9 \downarrow$	$3.2 \times 10^9 \downarrow$	$4.1 \times 10^9 \downarrow$	160	320	410
Compression set (9 per cent)	$1.8 \times 10^8 \circ$	$5 \times 10^8 \downarrow$	$1.3 \times 10^9 \downarrow$	18	50	130
Strain at 400 lb/in. ² (31 per cent)	$6.4 \times 10^8 \downarrow$	$3.6 \times 10^9 \downarrow$	$7.3 \times 10^9 \downarrow$	64	360	730
Shore hardness	4.1×10^9 (H = 78) \circ	9.1×10^9 (H = 83) \uparrow	1.4×10^{10} (H = 88) \uparrow	410	910	1400
Polysulfide Rubber (Thiokol ST)						
Tensile strength (800 psi)	$4.5 \times 10^7 \downarrow$	$8.2 \times 10^9 \downarrow$	$2.3 \times 10^{10} \downarrow$	41	820	2300
Elongation (162 per cent)	$4.5 \times 10^7 \downarrow$	$4.1 \times 10^8 \downarrow$	$5.5 \times 10^9 \downarrow$	4.5	41	1000
Set at break (3 per cent)	$4.5 \times 10^7 \downarrow$	$3.4 \times 10^8 \downarrow$	$1.6 \times 10^9 \downarrow$	4.5	34	160
Compression set (9 per cent)	$6.0 \times 10^7 \downarrow$	$1.4 \times 10^8 \downarrow$	$2.3 \times 10^8 \downarrow$	4.5	14	23
Strain at 400 lb/in. ² (26 per cent)	$4.5 \times 10^8 \downarrow$	$8.5 \times 10^9 \downarrow$	$1.1 \times 10^{10} \downarrow$	45	850	1100
Shore hardness	2.9×10^7 (H = 74) \uparrow	9.1×10^8 (H = 79) \uparrow	4.5×10^{10} (H = 69) \uparrow	2.4	240	4500
Silicone Rubber (Silastic 7-170)						
Tensile strength (520 psi)	$1.2 \times 10^8 \uparrow$	$4.9 \times 10^9 \downarrow$	$1.5 \times 10^{10} \downarrow$	12	490	1500
Elongation (95 per cent)	$1.4 \times 10^8 \downarrow$	$6.8 \times 10^8 \downarrow$	$1.6 \times 10^9 \downarrow$	14	68	160
Set at break	--	--	--	--	--	--
Compression set (1.4 per cent)	$1.2 \times 10^8 \downarrow$	$3.8 \times 10^8 \downarrow$	$9.1 \times 10^8 \downarrow$	12	38	91
Strain at 400 lb/in. ² (3.4 per cent)	$1.6 \times 10^8 \downarrow$	$1.2 \times 10^9 \downarrow$	$3.2 \times 10^9 \downarrow$	16	120	320
Shore hardness	1.2×10^8 (H = 59) \uparrow	4.2×10^8 (H = 64) \uparrow	8×10^8 (H = 69) \uparrow	12	42	66
Styrene-Butadiene Rubber (SBR) (GR-S 50)						
Tensile strength (1,700 psi)	$5 \times 10^9 \circ$	$2.7 \times 10^{10} \uparrow$	$4.8 \times 10^{10} \downarrow$	500	2700	4800
Elongation (270 per cent)	$1.8 \times 10^8 \downarrow$	$1.2 \times 10^9 \downarrow$	$4.5 \times 10^9 \downarrow$	18	120	450
Set at break (5 per cent)	$1.8 \times 10^8 \downarrow$	$1.2 \times 10^9 \downarrow$	$4.5 \times 10^9 \downarrow$	18	120	450
Compression set (4.7 per cent)	$1.8 \times 10^8 \downarrow$	$1.2 \times 10^9 \downarrow$	$5.5 \times 10^9 \downarrow$	18	120	550
Strain at 400 lb/in. ² (28 per cent)	$1.8 \times 10^8 \downarrow$	$1.5 \times 10^9 \downarrow$	6.8×10^9	18	150	680
Shore hardness	4.5×10^7 (H = 62) \uparrow	7×10^8 (H = 67) \uparrow	1.4×10^{10} (H = 72) \uparrow	4.5	100	1400

(a) The hours are calculated by dividing the total dose to produce damage by the energy-absorption rate [$(10^7 \text{ ergs g}^{-1} \text{ hr}^{-1} \text{ (C)})$]. Hours for other radiation rates can be similarly calculated. These values are relative only, and are not intended for use for service-life estimates.

(b) The symbols beside the dose values indicate whether the value is increasing (\uparrow), decreasing (\downarrow), or not changing (\circ).

(c) Doses for Shore hardness are noted for the values given rather than for threshold, 25 per cent, and 50 per cent damage.

TABLE 5. HOURS TO PRODUCE DAMAGE TO PLASTICS IN A FIELD
IN WHICH MATERIALS ABSORB 10^7 ERGS G^{-1} HR $^{-1}$ (a)

Material and Original Property Value	Absorbed Total Dose to Produce Damage, ergs g^{-1} (C)			Hours to Produce Indicated Damage to Plastics		
	Threshold Damage	25 Per Cent Damage	50 Per Cent Damage	Threshold Damage	25 Per Cent Damage	50 Per Cent Damage
<u>Acrylics</u>						
Methyl Methacrylate (Lucite)						
Tensile strength (10,700 psi)	7.5×10^7	10^9	2×10^9	7.5	100	200
Elongation (4.5 per cent)	7.5×10^7	10^9	2×10^9	7.5	100	200
Elastic modulus (4.8×10^5 psi)	1.4×10^9	5×10^9	--	140	500	--
Shear strength (6,700 psi)	10^9	4×10^9	6.2×10^9	100	400	620
Impact strength (0.37 ft-lb/in. of notch)	10^9	4×10^9	6.2×10^9	100	400	620
<u>Amino Resins</u>						
Aniline Formaldehyde (Cibanite)						
Tensile strength (9,200 psi)	9.1×10^9	2.4×10^{11}	3.6×10^{11}	910	24,000	36,000
Elongation (1.8 per cent)	9.1×10^9	2.4×10^{11}	3.6×10^{11}	910	24,000	36,000
Elastic modulus (6.0×10^5 psi)	4.2×10^{11}	--	--	42,000	--	--
Shear strength (9,700 psi)	9.1×10^9	2.4×10^{11}	3.6×10^{11}	910	24,000	36,000
Impact strength (0.20 ft-lb/in. of notch)	6.7×10^7	1.3×10^9	1.2×10^{10}	6.7	130	1,200
Melamine Formaldehyde (Melmac)- Cellulose Filler						
Tensile strength (9,000 psi)	6.7×10^8	6.6×10^9	1.6×10^{10}	67	660	1,600
Elongation (0.65 per cent)	6.7×10^8	6.6×10^9	1.6×10^{10}	67	660	1,600
Elastic modulus (14×10^5 psi)	10^{10}	1.3×10^{11}	--	1,000	13,000	--
Shear strength (10,000 psi)	6.7×10^8	3.9×10^{10}	9.1×10^{10}	67	3,900	9,100
Impact strength (0.30 ft-lb/in. of notch)	9.1×10^{10}	2.2×10^{11}	2.5×10^{11}	9,100	22,000	25,000
Urea Formaldehyde (Plaskon Urea)- Cellulose Pulp Pigment						
Tensile strength (7,800 psi)	7.5×10^8	3×10^9	7.3×10^9	75	460	730
Elongation (0.5 per cent)	7.5×10^8	3×10^9	7.3×10^9	75	460	730
Elastic modulus (14×10^5 psi)	3.2×10^9	2.7×10^{10}	--	320	2,700	--
Shear strength (10,000 psi)	7.5×10^8	3×10^9	7.3×10^9	75	460	730
Impact strength (0.30 ft-lb/in. of notch)	3.2×10^9	5.8×10^{10}	8.2×10^{10}	320	5,800	8,200

TABLE 5. (Continued)

Material and Original Property Value	Absorbed Total Dose to Produce Damage, $\text{ergs g}^{-1}(\text{C})$			Hours to Produce Indicated Damage to Plastics		
	Threshold Damage	25 Per Cent Damage	50 Per Cent Damage	Threshold Damage	25 Per Cent Damage	50 Per Cent Damage
<u>Furane Resins</u>						
Furane Resin (Duralon)- Asbestos and Carbon- Black Filler						
Tensile strength (2,200 psi)	3×10^{10}	3×10^{11}	--	3,000	30,000	--
Elongation (0.39 per cent)	3×10^{10}	3×10^{11}	--	3,000	30,000	--
Elastic modulus (8×10^5 psi)	3×10^{10}	3×10^{11}	--	3,000	30,000	--
Impact strength (0.31 ft-lb/in. of notch)	3×10^{10}	3×10^{11}	--	3,000	30,000	--
<u>Phenolics</u>						
Phenol Formaldehyde (Havag 41)- Asbestos Filler						
Tensile strength (3,500 psi)	3.5×10^{10}	3.5×10^{11}	--	3,500	35,000	--
Elongation (0.5 per cent)	3.5×10^{10}	3.5×10^{11}	--	3,500	35,000	--
Elastic modulus (10×10^5 psi)	3.5×10^{10}	3.5×10^{11}	--	3,500	35,000	--
Impact strength (0.31 ft-lb/in. of notch)	3.5×10^{10}	3.5×10^{11}	--	3,500	35,000	--
<u>Polyesters</u>						
Polyester (Plaskon Alkyd)- Mineral Filler						
Tensile strength (4,700 psi)	7.9×10^9	3.5×10^{11}	--	790	35,000	--
Elongation (0.17 per cent)	7.9×10^9	3.5×10^{11}	--	790	35,000	--
Elastic modulus (32×10^5 psi)	7.9×10^9	3.5×10^{11}	--	790	35,000	--
Shear strength (7,000 psi)	7.9×10^9	3.5×10^{11}	--	790	35,000	--
Impact strength (0.39 ft-lb/in. of notch)	7.9×10^9	3.5×10^{11}	--	790	35,000	--
<u>Styrene Polymers and Copolymers</u>						
Polystyrene (Styron 411-C)-White Pigment Filler						
Tensile strength (4,400 psi)	7.3×10^{10}	3.6×10^{11}	--	7,300	36,000	--
Elongation (1.0 per cent)	7.3×10^{10}	3.6×10^{11}	--	7,300	36,000	--
Elastic modulus (4.8×10^5 psi)	7.3×10^{10}	3.6×10^{11}	--	7,300	36,000	--
Shear strength (5,500 psi)	7.3×10^{10}	3.6×10^{11}	--	7,300	36,000	--
Impact strength (0.20 ft-lb/in. of notch)	7.3×10^{10}	3.6×10^{11}	--	7,300	36,000	--

TABLE 5. (Continued)

Material and Original Property Value	Absorbed Total Dose to Produce Damage, ergs g ⁻¹ (C)			Hours to Produce Indicated Damage to Plastics		
	Threshold Damage	25 Per Cent Damage	50 Per Cent Damage	Threshold Damage	25 Per Cent Damage	50 Per Cent Damage
<u>Cellulosics</u>						
Cellulose Acetate Butyrate (Tenite II)						
Tensile strength (4,200 psi)	1.6×10^8 †	2.3×10^9 †	3.3×10^9 †	16	230	330
Elongation (60 per cent)	1.6×10^8 †	2.3×10^9 †	3.3×10^9 †	16	230	330
Elastic modulus (1.6×10^5 psi)	3.4×10^7 †	3.2×10^9 † (20% damage)	--	3.4	320	--
Shear strength (4,000 psi)	1.6×10^8 †	2.3×10^9 †	3.3×10^9 †	16	230	330
Impact strength (3.3 ft-lb/in. of notch)	6.8×10^7 †	6.6×10^8 †	1.9×10^9 †	6.8	66	190
<u>Ethylene Polymers</u>						
Polyethylene (Polythene)						
Tensile strength (1,400 psi)	1.7×10^9 †	7.3×10^{11} †	--	170	73,000	--
Elongation (250 per cent)	2.1×10^9 †	8.5×10^9 †	1.6×10^{10} †	210	850	1,600
Elastic modulus (0.30×10^5 psi)	3.6×10^{10} †	1.3×10^{11} †	1.8×10^{11} †	3,600	13,000	18,000
Shear strength (1,400 psi)	1.7×10^9 †	9.1×10^9 †	2.9×10^{10} †	170	910	2,900
Impact strength (11.2 ft-lb/in. of notch)	2.1×10^9 †	8.5×10^9 †	1.6×10^{10} †	210	850	1,600
<u>Fluoroethylene Polymers</u>						
Monochlorotrifluoroethylene (Fluorothene)						
Tensile strength (4,900 psi)	1.6×10^9 †	4.2×10^9 †	1.1×10^{10} †	360	820	1,100
Elongation (50 per cent)	3.6×10^8 †	1.8×10^9 †	4.1×10^9 †	12	180	410
Elastic modulus (1.8×10^5 psi)	1.2×10^8 †	1.5×10^{10} †	--	12	1,500	--
Shear strength (5,100 psi)	1.2×10^8 †	1.5×10^{10} †	2×10^{10} †	12	1,500	2,900
Impact strength (1.9 ft-lb/in. of notch)	3.6×10^8 †	1.8×10^9 †	4.1×10^9 †	12	180	410
Polytetrafluoroethylene (Teflon)						
Tensile strength (3,400 psi)	2.1×10^6 †	1.2×10^7 †	9.1×10^7 †	0.2	1.2	9
Elongation (250 per cent)	1.5×10^6 †	3.4×10^6 †	7.3×10^6 †	0.15	0.3	0.6
Elastic modulus (1.0×10^5 psi)	1.8×10^7 †	2.3×10^9 † (20% damage)	--	1.8	230	--
Shear strength (2,800 psi)	1.8×10^7 †	4×10^7 †	1.5×10^8 †	1.8	4	15
Impact strength (3.3 ft-lb/in. of notch)	1.8×10^7 †	3.6×10^7 †	5×10^7 †	1.8	3.6	5

TABLE 5. (Continued)

Material and Original Property Value	Absorbed Total Dose to Produce Damage, ergs g ⁻¹ (C)			Hours to Produce Indicated Damage to Plastics		
	Threshold Damage	25 Per Cent Damage	50 Per Cent Damage	Threshold Damage	25 Per Cent Damage	50 Per Cent Damage
Vinyl Polymers and Copolymers						
Polyvinyl Carbazole (Polycarbon)						
Tensile strength (1,800 psi)	8×10^9	0.4×10^{11}	o	800	40,000	—
Elongation (0.5 per cent)	8×10^9	0.4×10^{11}	o	800	40,000	—
Elastic modulus (5.8×10^5 psi)	8×10^9	0.4×10^{11}	o	800	40,000	—
Shear strength (3,500 psi)	8×10^9	0.4×10^{11}	o	800	40,000	—
Impact strength (0.19 ft.-lb./in. of notch)	8×10^9	0.4×10^{11}	o	800	40,000	—
Polycvinyl Chloride (Geon 2046)						
Tensile strength (2,800 psi)	4.1×10^{10} †	1.7×10^{11} †	3.7×10^{11} †	4,100	17,000	37,000
Elongation (310 per cent)	1.7×10^9 †	10^{10} †	3.7×10^{10} †	170	1,000	3,700
Vinyl Vinylidene Chloride (Saran)						
Tensile strength (3,700 psi)	6.4×10^8 †	1.6×10^{10} †	8.2×10^{10} †	64	1,600	8,200
Elongation (200 per cent)	3.7×10^9 †	4.1×10^9 †	1.6×10^{10} †	37	410	1,600
Elastic modulus (0.65×10^5 psi)	6.4×10^8 †	7.3×10^{10} †	1.4×10^{11} †	64	7,300	14,000
Shear strength (2,900 psi)	4.1×10^9 †	6.5×10^{10} †	1.2×10^{11} †	410	6,500	12,000
Impact strength (1.6 ft.-lb./in. of notch)	3.7×10^8 †	4.1×10^9 †	1.6×10^{10} †	37	410	1,600

(†) Hours are calculated by dividing the total dose to produce damage by the rate of energy absorption (10^7 ergs g⁻¹hr⁻¹(C)). Hours for other radiation rates can be similarly calculated. These values are relative only, and are not intended for use for service life estimates.

(o) Symbols beside the dose values indicate whether the value is increasing (↑), decreasing (↓), or not changing (o).

Elevated Temperature

Studies have shown that for a particular polymer system, the more heat-resistant materials are more resistant to degradation from nuclear radiation. Also, with some heat-resistant materials, radiation damage is similar regardless of exposure temperature. For example, it has been reported that there were no observed differences in deterioration of Teflon, Kel-F, and a polydimethyl siloxane when irradiated from 101 to 313 F. (7)

On irradiation at 300 F, the fluorine-containing rubbers, Viton A-VH and Silastic LS-53, liberated a corrosive chemical, probably hydrofluoric acid. For this reason, fluorine rubbers should not be used in a radiation field above 300 F if corrosion is a problem.

The curing system and the reactive diluent used in epoxy resins have a large effect on the heat resistance and radiation stability of the resins. In general, epoxy resins of high heat-distortion temperatures are more resistant to radiation than those having lower temperature resistance. Anhydride curing systems produce epoxy plastics having high heat-distortion temperatures. In one such system, after a radiation dose of 10^{10} ergs g^{-1} (C), the heat-distortion temperature decreased from 575 F to approximately 500 F.

Buna-N and Teflon were tested under simulated operating conditions up to 350 F. (8) Buna-N was affected less by radiation and appeared to function satisfactorily at exposure doses up to about 4×10^8 ergs g^{-1} (C), at temperatures up to 350 F and static pressures of 1,200 psig. An intermittent test (0 to 1,000 psig) at 350 F indicated Buna-N to be satisfactory to at least 10^8 ergs g^{-1} (C). The Teflon material failed at lower exposure doses - about 10^8 ergs g^{-1} (C) for static pressure and 10^7 ergs g^{-1} (C) for intermittent pressure. The exposure dose-failure relationship was practically independent of temperature from 100 to 350 F.

The effects of simultaneous exposure of both gamma radiation and elevated temperature on glass-reinforced plastic laminates have been investigated. In general, the mechanical and electrical properties of reinforced plastic laminates of various resin types were not adversely affected by gamma radiation of a maximum dose of 7.8×10^{10} ergs g^{-1} (C). Threshold damage was reached at 8.3×10^{11} ergs g^{-1} (C), with the exception of a phenolic resin (CTL-91LD) laminate which retained useful properties even after exposure to this large radiation dose. Keller⁽⁹⁾ pointed out that a phenolic system ordinarily deteriorates when exposed to elevated temperatures in the presence of air due to oxidation. He suggested that it is possible that irradiation inhibits the oxidation and that crosslinking takes place. The results of these tests are summarized in Tables 6 and 7 and graphically in Figures 7, 8, and 9.

Commercially available adhesives were investigated to determine the effect of gamma radiation on their strength properties, at both room and elevated temperatures. In general, most of the adhesives showed a loss of one-third their initial strength at approximately 5×10^{10} ergs g^{-1} (C), while one adhesive had very little loss in strength with an exposure of nearly 10^{11} ergs g^{-1} (C). Strength degradation occurred earliest in the least heat-resistant adhesives. A heat-resistant epoxy-phenolic adhesive, Epon 422, was essentially unaffected by gamma radiation at all testing temperatures. (10)

TABLE 6. PERCENTAGE OF STRENGTH RETENTION OF HEAT-RESISTANT LAMINATES AT VARIOUS EXPOSURE LEVELS

Resin	Exposure Level, ergs g ⁻¹ (C)	Strength Retention, per cent				
		Tensile, 2-Hour Boil	Compressive, 2 Hour Boil	Flexure, 2-Hour Boil	Compressive, 1/2 Hour at 500 F	Flexure, 1/2 Hour at 500 F
TAC-Polyester	8.3 x 10 ¹⁰	100	79	100	86	73
TAC-polyester	2.49 x 10 ¹¹	100	76	86	18	52
TAC-polyester	8.3 x 10 ¹¹	75	53	48	21	50
Phenolic	8.3 x 10 ¹⁰	100	100+	100+	100+	100+
Phenolic	2.49 x 10 ¹¹	95	100+	100+	100+	100+
Phenolic	8.3 x 10 ¹¹	100+	100+	100+	55	100+
Silicone	8.3 x 10 ¹⁰	100+	100+	50	100+	100+
Silicone	2.49 x 10 ¹¹	100+	75	37	100	100+
Silicone	8.3 x 10 ¹¹	76	Too pliable to test	7	55	100+
Heat-resistant epoxy	8.3 x 10 ¹⁰	100+	100+	100+	75	54
Heat-resistant epoxy	2.49 x 10 ¹¹	100+	46	70	47	43
Heat-resistant epoxy	8.3 x 10 ¹¹	97	12	27	25	32

TABLE 7. MECHANICAL PROPERTIES OF GLASS FABRIC-REINFORCED PLASTIC LAMINATES AFTER IRRADIATION AT ELEVATED TEMPERATURE(a)

Material	Test	Radiation, 10 ⁹ ergs g ⁻¹ (C)	Temperature, F	Exposure Time, hr	Ultimate Strength, psi	Flexural Modulus, 10 ⁶ psi
Silicone	Flexure	None	Room	None	37,700	3.00
		8.3	Room	200	31,400	2.04
		None	500	50	12,300	1.90
		2.1	500	50	13,025	2.0
		None	500	100	13,410	2.0
		4.15	500	100	11,720	2.0
		None	500	200	14,060	2.0
		8.3	500	200	9,800	1.9
Heat-resistant epoxy	Compression	None	Room	None	40,080	
		8.3	Room	200	40,080	
		None	500	50	3,705	
		2.1	500	50	3,780	
		None	500	100	4,090	
		4.15	500	100	5,490	
		None	500	200	4,720	
		8.3	500	200	6,360	
Phenolic	Flexure	None	Room	None	34,525	4.22
		8.3	Room	200	24,040	4.35
		None	500	50	27,300	3.14
		2.1	500	50	55,020	3.46
		None	500	100	17,660	2.62
		4.15	500	100	47,015	3.61
		None	500	200	12,330	2.13
		8.3	500	200	15,645	2.41

(a) Simultaneous radiation and temperature exposure.

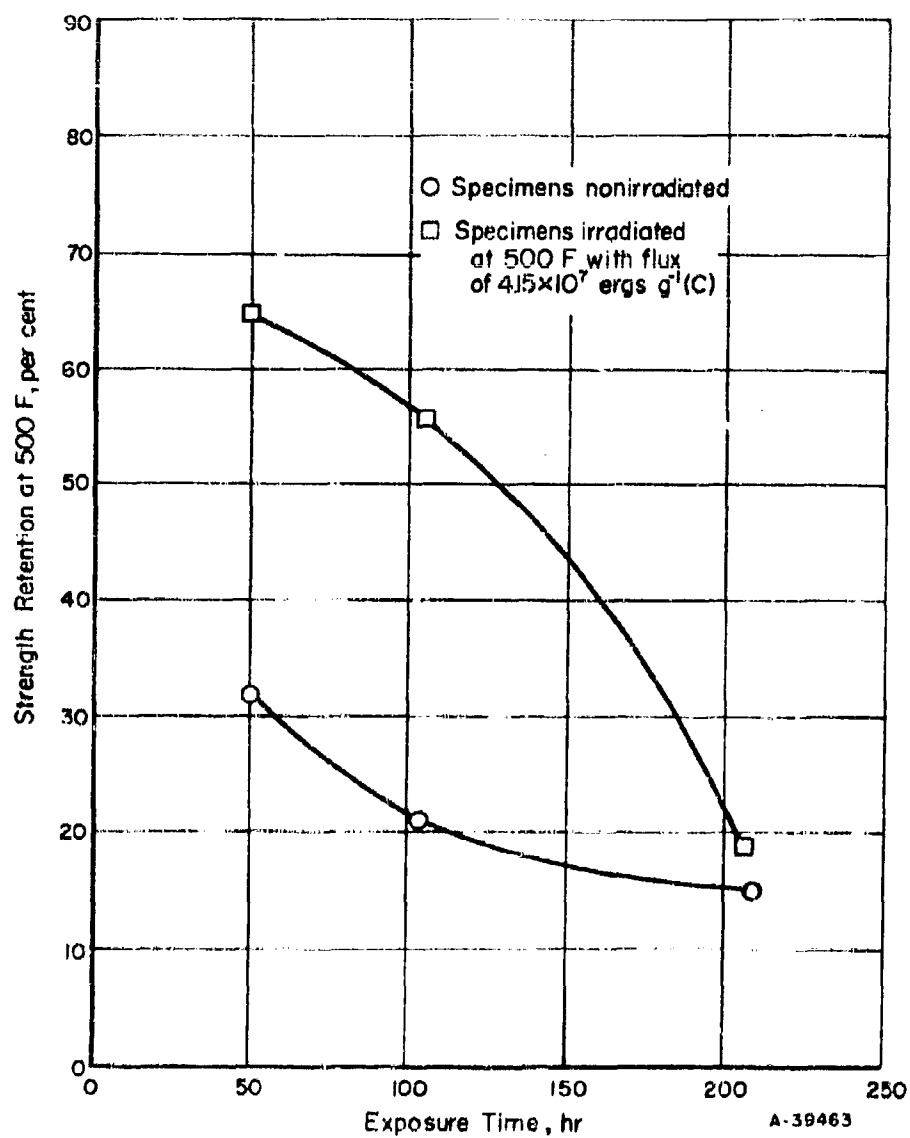


FIGURE 7. EFFECTS OF IRRADIATION AT ELEVATED TEMPERATURE ON PHENOLIC LAMINATE

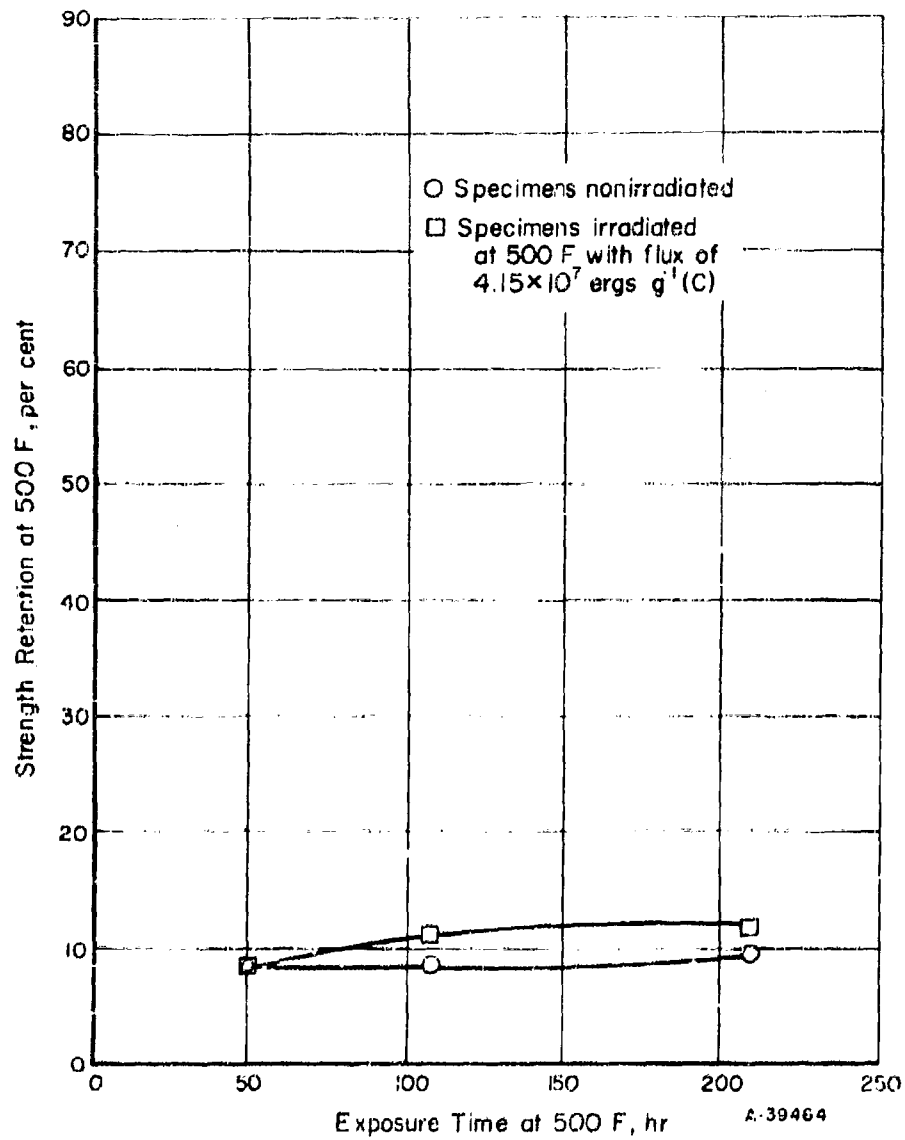


FIGURE 8. EFFECTS OF IRRADIATION AT ELEVATED TEMPERATURE ON HEAT-RESISTANT EPOXY LAMINATE

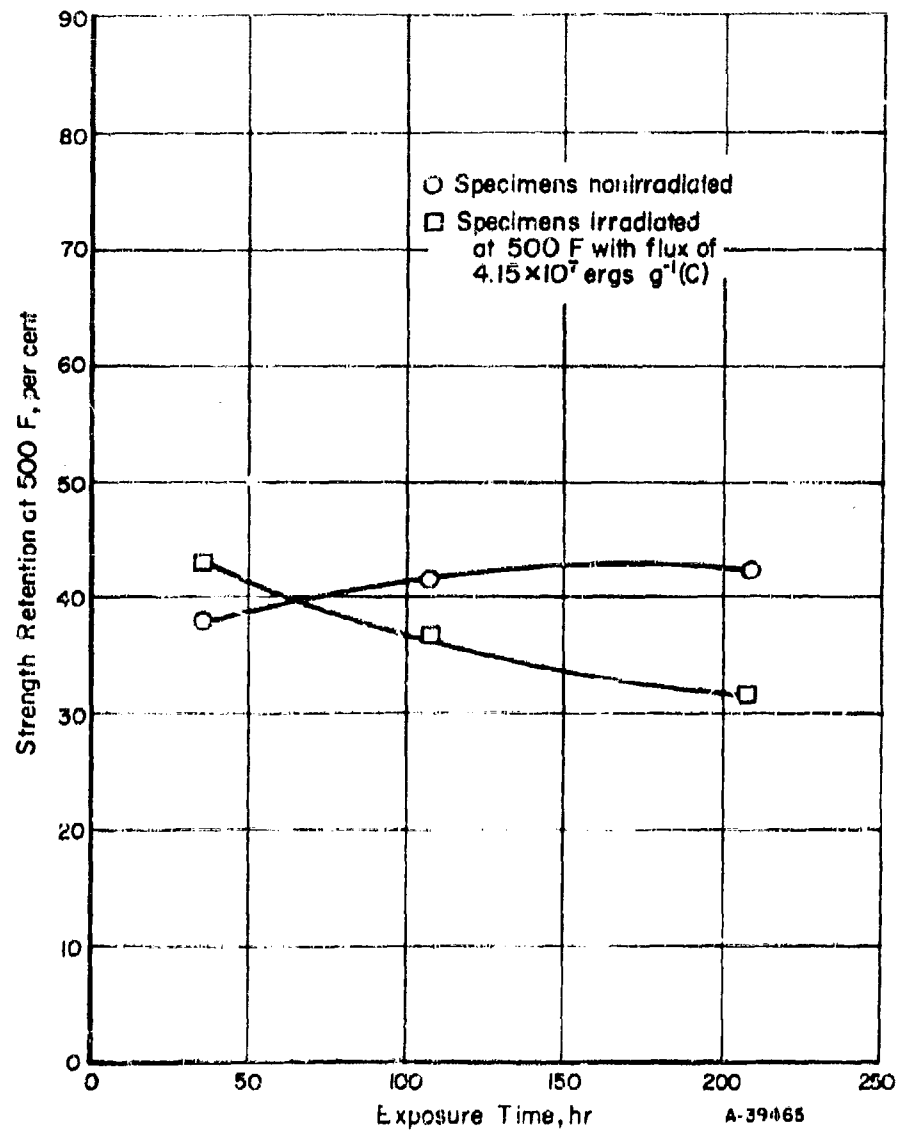


FIGURE 9. EFFECTS OF IRRADIATION AT ELEVATED TEMPERATURE ON SILICONE LAMINATE

Workers at B. F. Goodrich Company⁽¹¹⁾ irradiated nitrile and neoprene rubbers at 158 F and found that the effect of the combined temperature and radiation was not appreciably different from the effect of radiation alone. However, it is expected that, at higher temperatures, more rapid deterioration will take place.

Liquids and Gases

Seals and gaskets have been found to be more radiation resistant when immersed in oil and, as a result, seals of Viton A, silicone, or nitrile rubber are now believed capable of service to an exposure dose of 10^{10} ergs g^{-1} (C), whereas, on the basis of static tests in air, an exposure dose of 10^8 ergs g^{-1} (C) has been considered maximum.

In irradiation studies of fluorocarbon elastomers, it was found that many of them behave differently on irradiation in diester fluid than in air. When irradiated in air, Viton A and Elastomer 214 began to get soft and tacky at 6×10^8 ergs g^{-1} (C), but survived 1×10^{10} ergs g^{-1} (C) in diester oil at 400 F with retention of rubberlike properties.⁽¹²⁾ In argon gas, however, an exposure to 5×10^8 ergs g^{-1} (C) at 400 F caused 75 per cent loss of tensile strength and elongation. At 500 F, the same dose caused a complete loss of useful properties. It has been suggested that petroleum (and perhaps other oils) may be a natural protective agent against gamma radiation by acting as a scavenger for free radicals or by providing an effective medium for energy transfer.

Viton A O-rings were irradiated at 400 F while immersed in MLO-8200 and Versilube F-50 hydraulic fluids.⁽¹³⁾ Samples retained most of their elastomeric properties and sealing abilities at 8.4×10^8 ergs g^{-1} (C). They became considerably harder but still retained their sealing ability at 8.4×10^9 ergs g^{-1} (C). Exposure to 8.4×10^{10} ergs g^{-1} (C) caused the O-rings to become very hard and brittle and to lose their sealing ability. Those irradiated in MLO-8200 sealed better under all test conditions than those irradiated in Versilube F-50.

Viton A O-rings were irradiated at 5×10^9 ergs g^{-1} (C) while immersed in Oronite 8200 hydraulic fluid at a temperature of 200 F and pressures up to 3,000 psi.⁽¹⁴⁾ Some leakage during the final stages of the test was noted. In subsequent tests in Oronite 8515 at 275 F and 3,000 psi, similar seals leaked and did not perform satisfactorily at an average radiation dose rate of 1.1×10^7 ergs g^{-1} (C) hr^{-1} [3×10^9 ergs g^{-1} (C)].⁽¹⁵⁾

Viton A, nitrile rubber, neoprene, and a fluorinated silicone (LS-53), were tested at temperatures ranging from 190 to 300 F and at a gamma dose of 1.75×10^8 ergs g^{-1} (C).⁽¹⁶⁾ These were tested separately in MIL-F-7-24 fuel, MIL-L-7808C lubricant, and a high-temperature hydraulic fluid, OS-45, under pressures ranging from 0 to 1,000 psig. There were no elastomer failures during these 200-hour tests.

Viton A-asbestos backup rings were found satisfactory for use in a flight-control system operating at 200 F using MLO-8200 hydraulic fluid and at an exposure dose of 8.8×10^9 ergs g^{-1} (C).⁽¹⁴⁾

Neoprene O-rings containing an antirad suffered 10 per cent less change in elongation than a standard compound after irradiation in air and in a pressure vessel containing Oronite 8515 at 350 F and 3000 psi for 14 hours.⁽¹⁷⁾

Commercially available Thiokol sealants were irradiated in air and in JP-4 fuel.⁽¹⁷⁾ The sealants irradiated in fuel showed more reduction in tensile strength and elongation

than those irradiated in air. Thiokol sealants having a high filler content were less radiation resistant than controls when irradiated in fuel. This decreased resistance with fillers has also been noted in elastomers irradiated in fuel.

Thiokol sealants were irradiated at 140 F at three different doses while immersed in JP-4 fuel. Under these conditions, the sealants were resistant to a dose of 3.5×10^9 ergs g^{-1} (C) but were unsatisfactory at 1×10^{10} ergs g^{-1} (C).

Vacuum

Very little information is available regarding radiation effects in a high vacuum. However some studies have been made in different vacuum applications and results are summarized below.

The vacuum-sealing properties of silicones have been determined during irradiation. The data showed that dimethyl silastic compound retained flexibility and maintained a vacuum seal to 2×10^{11} ergs g^{-1} (C) even though its physical properties were degraded. (18)

Silastics 160 and 181 were bombarded with deuterons while being used as a seal. The amount of energy absorbed in the last test where a vacuum seal held was 2×10^{11} ergs g^{-1} (C) for both materials. The vacuum seal failed to hold when 1.1×10^{12} ergs g^{-1} (C) was absorbed by Silastic 160 and when 3.7×10^{11} ergs g^{-1} (C) was absorbed by Silastic 181.

Nylon tire cords lose more than 50 per cent of their original tensile strength when irradiated in air at 8.5×10^8 ergs g^{-1} (C). (19) When irradiated in a vacuum to the same exposure dose, these fibers decrease less than 15 per cent in tensile strength. Elongation increased from 1 to 20 per cent when irradiated in a vacuum as compared with a decrease of 50 per cent when irradiated in air. The flex-life of the fibers decreased rapidly when exposed in air. Thus, oxygen is a strong contributor to the degradation of physical properties of nylon in the presence of radiation.

Irradiation of Mylar in vacuum to 8.7×10^9 ergs g^{-1} (C) produced the same damage as 4.4×10^9 ergs g^{-1} (C) in air, indicating that oxidation plays some role in the damage induced. (20)

As determined from tests on reinforced plastic laminates, the combined effects of high vacuum, ultraviolet radiation, and elevated temperatures are not significant on most structural plastic materials. The extent of degradation in epoxy and phenolic laminates is a function of temperature rather than high vacuum or combined high vacuum and temperature. Exposure conditions in these tests were a radiant-energy flux concentrated in the range from 2500 to 5800 Å but equivalent in amount to the solar constant, temperatures of 300 F, and reduced pressures of 10^{-6} to 10^{-7} mm Hg.

EFFECT OF DOSE RATE ON POLYMERS

The damage to a polymer by radiation is generally dependent on total dose absorbed regardless of type of radiation. Questions often arise as to dose-rate effects. Extensive dose-rate studies have been made. The data that are available are presented below.

Aitken, Ralph, and Sheldon⁽²¹⁾ irradiated epoxy resins, using a pile, a spent fuel assembly (gamma), and a linear accelerator (electrons). In the pile, the specimens were irradiated in air at room temperature (70 C) and a thermal neutron flux of $1.2 \times 10^{14} \text{ n cm}^{-2} \text{ sec}^{-1}$ using a pile factor of $10^{17} \text{ nvt} = 7 \times 10^7 \text{ rads}$. Doses of 1.2×10^8 , 8.5×10^8 , 1.3×10^9 , and $2.9 \times 10^9 \text{ rads}$ were received, at a dose rate of $2.9 \text{ megarads hr}^{-1}$.

In the spent fuel assembly, the specimens were irradiated in air at room temperature using a dose rate of $2.0 \text{ megarads hr}^{-1}$ gamma, together with $10^3 \text{ thermal n cm}^{-2} \text{ sec}^{-1}$. The latter were neglected as insignificant since thermal neutrons have not been found to contribute to the degradation of simple polymers. In the linear accelerator the specimens were again irradiated in air at room temperature at a dose rate of $1.8 \times 10^2 \text{ megarad hr}^{-1}$.

The results from pile and gamma irradiation were in reasonable agreement with each other. This was not so in the case of the electron irradiation. This discrepancy is probably due to the wide differences in dose rates used; $2.92 \text{ megarad hr}^{-1}$ in the pile, $2.0 \text{ megarad hr}^{-1}$ in the spent fuel assembly, against $1.8 \times 10^2 \text{ megarad hr}^{-1}$ with the linear accelerator.

Dose rate does seem to have an important bearing on the processes, when the samples react with their surroundings. In the case of irradiations carried out in air, the degradation processes may be regarded as being due to the diffusion of oxygen into the specimens, which yields peroxidation and hydroperoxidation of the radicals. The degree to which these reactions affect the physical properties of the material is probably dependent on the diffusion rate of oxygen in the matrix and on the geometry of the specimen. In the case of electron irradiations, the dose rate (free-radical production) may be in excess of the diffusion rate of oxygen, causing the crosslinking reactions to predominate. In the case of the gamma and pile irradiations, free-radical production rate is sufficiently low to allow the diffusion of oxygen to influence the degradative process - causing chain shortening and inhibition of crosslinking.

The results of experimental irradiations at high dose rates in air should be treated with extreme caution. The time scale of irradiation should be sufficiently long to allow secondary processes to occur to their full extent, before the results obtained can be related to the materials under working conditions.

Radiation in Van Allen belts is a mixture of electrons and protons existing in two major belts surrounding the earth. The Pioneer vehicle space probes indicated that maximum intensity in the Van Allen space radiation belts surrounding the earth was approximately 100 roentgens/hour and then only if the radiation consisted of protons, which would be the worst possible case.⁽²²⁾ Thus, maximum total dose sustained by a space vehicle in one year would be $8.7 \times 10^5 \text{ roentgens}$, and then only if the vehicle remained in the center of the radiation belt continuously. Hence, a number of the polymers may be serviceable for at least a year.

FUNDAMENTAL STUDIES

There has recently been an increase in the number of fundamental studies directed toward the development or testing of elastomers and plastics. Three of these studies are of significance to those interested in developing radiation-resistant elastomers.

The first study of this type is in connection with the determination of combined heat and radiation stability of polymers. General Electric⁽²³⁾ derived an equation from photochemical principles which may apply to many materials under combined radiation and temperature conditions.

The general formula is

$$\ln t = \frac{K_1}{T} - \left(\frac{K_2}{T} + K_3 \right) \ln r + K_4,$$

where

t = time to failure in hours

T = absolute temperature in degrees Kelvin

r = radiation-exposure rate in ergs g^{-1} (C) hr^{-1}

K_1 , K_2 , K_3 , and K_4 are constants determined experimentally.

Tests were made on Teflon to check the applicability of this relationship with respect to organic solids.

The dynamic test used consisted of flexing during irradiation at temperature with samples under tensile stress and exposed to either an oil or air environment. The test was continued until the samples failed by breaking.

The results of the Teflon tests were found to obey the expected type of relationship. The performance of the material differed in the temperature regions below and above 250 F. This type of behavior occurs under nonradiation conditions and usually is attributable to a phase change or to the predominance of different reactions in the two temperature ranges.

The empirical equations applicable to the results of the Teflon tests are:

(1) For temperatures less than 250 F

$$\ln t = \frac{1576.1}{T} - \left(\frac{66.79}{T} + 0.64064 \right) \ln r + 10.8841$$

(2) For temperatures above 250 F

$$\ln t = \frac{5825.7}{T} - \left(\frac{190.3}{T} + 0.33148 \right) \ln r + 0.16639 .$$

Excellent agreement between calculated and experimental values was obtained.

The second study involves The B. F. Goodrich Company's⁽²⁴⁾ monomer-synthesis program to show the effects of the relative position of aromatic ring structures in polymers on the degree of radiation protection. Acrylate monomers have been selected for study because they produce fairly heat-resistant polymers and can be polymerized using familiar techniques.

Four groups of monomers are being synthesized or purchased. The chemical structures of these monomers are shown in Table 8.

TABLE II. MONOMERS FOR STUDIES ON THE EFFECT OF POSITION OF PHENYL GROUPS IN POLYMERS ON RADIATION STABILITY (24)

GROUP I	GROUP II
$\text{CH}_2=\text{CH}-\text{C}\begin{matrix} \text{O} \\ \parallel \\ \text{O}-\text{C}_2\text{H}_5 \end{matrix}$ <p>Ethyl acrylate</p>	$\text{CH}_2=\text{C}\begin{matrix} \text{O} \\ \parallel \\ \text{O}-\text{C}_2\text{H}_5 \end{matrix}-\text{C}_6\text{H}_5$ <p>Ethyl-α-phenyl acrylate</p>
$\text{CH}_2=\text{CH}-\text{C}\begin{matrix} \text{O} \\ \parallel \\ \text{O}-\text{C}_6\text{H}_5 \end{matrix}$ <p>Phenyl acrylate</p>	$\text{CH}_2=\text{C}\begin{matrix} \text{O} \\ \parallel \\ \text{O}-\text{C}_6\text{H}_5 \end{matrix}-\text{C}_6\text{H}_5$ <p>Phenyl-α-phenyl acrylate</p>
$\text{CH}_2=\text{CH}-\text{C}\begin{matrix} \text{O} \\ \parallel \\ \text{O}-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{C}_6\text{H}_5 \end{matrix}$ <p>4-Phenyl butyl acrylate</p>	$\text{CH}_2=\text{CH}-\text{C}\begin{matrix} \text{O} \\ \parallel \\ \text{O}-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{C}_6\text{H}_5 \end{matrix}-\text{C}_6\text{H}_5$ <p>4-Phenyl butyl-α-phenyl acrylate</p>
GROUP III	GROUP IV
$\text{CH}_2=\text{C}\begin{matrix} \text{O} \\ \parallel \\ \text{O}-\text{C}_2\text{H}_5 \end{matrix}-\text{C}(\text{CH}_3)_2$ <p>Ethyl methacrylate</p>	$\text{CH}_2=\text{C}\begin{matrix} \text{O} \\ \parallel \\ \text{O}-\text{C}_2\text{H}_5 \end{matrix}-\text{C}(\text{CH}_2)_4-\text{C}_6\text{H}_5$ <p>Ethyl-α-(4-phenyl butyl) acrylate</p>
$\text{CH}_2=\text{C}\begin{matrix} \text{O} \\ \parallel \\ \text{O}-\text{C}_6\text{H}_5 \end{matrix}-\text{C}(\text{CH}_3)_2$ <p>Phenyl methacrylate</p>	$\text{CH}_2=\text{C}\begin{matrix} \text{O} \\ \parallel \\ \text{O}-(\text{CH}_2)_4-\text{C}_6\text{H}_5 \end{matrix}-\text{C}(\text{CH}_2)_4-\text{C}_6\text{H}_5$ <p>4-Phenyl butyl-α-(4-phenyl butyl) acrylate</p>
$\text{CH}_2=\text{C}\begin{matrix} \text{O} \\ \parallel \\ \text{O}-(\text{CH}_2)_4-\text{C}_6\text{H}_5 \end{matrix}-\text{C}(\text{CH}_3)_2$ <p>4-Phenyl butyl methacrylate</p>	$\text{CH}_2=\text{C}\begin{matrix} \text{O} \\ \parallel \\ \text{O}-\text{C}_6\text{H}_5 \end{matrix}-\text{C}(\text{CH}_2)_4-\text{C}_6\text{H}_5$ <p>Phenyl-γ-(4-phenyl butyl) acrylate</p>

Because of the various positions of the phenyl groups, Goodrich workers hope to determine⁽²⁴⁾:

- (1) The influence of distance of aromatic groups from the nearest reactive site on the rate of radiation-induced crosslinking (Group I) or chain scission (Group III)
- (2) The decrease in rate of chain scission when a methyl group attached to a carbon atom which also is connected to another group by a double bond (such as in polyethyl methacrylate) is replaced by a phenyl group (such as in polyethyl-alpha-phenyl acrylate)
- (3) The decrease in the latter protective effect as the distance of the phenyl group from the main chain increases (Group IV)
- (4) The importance of the intramolecular distance of the aromatic ring from a site of probable crosslinking or chain scission upon radiation resistance
- (5) The relative effect of multiple substitution with aromatic rings near a probable reactive site.

The third fundamental study of interest is being conducted by Convair⁽¹⁷⁾ on the effect of sample size, shape, and composition on the amount of energy absorbed from a beam of monoenergetic neutrons. The effect of sample composition was studied by determining whether the energy absorbed by a compound could be calculated using a simple additive process on data obtained for samples composed of only one element. They found that this additive process can be considered valid over rather wide ranges of composition, provided the elemental data are obtained from samples similar in size and shape to the sample under consideration.

The effect of sample shape on energy absorption was also studied. Right circular cylinders and rectangular parallelepipeds appeared to be equivalent, but spheres absorbed less energy by a factor of about 1.6. Other factors found to be important in estimating absorption are anisotropic scattering and cross-section resonances. Neglect of these factors resulted in underestimating energy absorbed by a factor of about 8.3.

SOVIET STUDIES ON RADIATION EFFECTS ON POLYMERIC MATERIALS

The Soviets are studying the effects of radiation on polymers and their published information has been reviewed for REIC. In most cases, this published information has contained little radiation-effects data unfamiliar to U. S. scientists. However, recently, Dubrovin and co-workers⁽²⁵⁾ studied the effects of radiation on some compositions containing sodium-polymerized butadiene which are used for Soviet cable insulation. This work is of interest because the compositions are different from those used in the U. S. and also because the radiation resistance of present cable insulation is not satisfactory for some applications.

The Soviet work described by Dubrovin included the effects of radiation on sodium butadiene, polychloroprene, and Buna-S rubbers. The compositions of these rubbers

are shown in Table A-1. The data given in Table A-2 show that the tensile properties of a vulcanizate based on Buna-S plus lithium-polymerized butadiene (ShBM-40) steadily increase as the radiation dose is increased. The tensile properties of two polychloroprene-based rubbers (NShI-35 and ShN-40) pass through a slight minimum (10 to 15 per cent lower than the initial) at 8.7×10^9 ergs g^{-1} (C) (100 mr). The strength of the sodium-butadiene rubbers decreases much more rapidly. These three vulcanizates, however, have a much greater breaking elongation than the other rubbers studied. Judging from its tensile properties, Buna-S plus lithium-polymerized butadiene has the greatest radiation stability, which is apparently due to the presence of phenyl groups. Data given in Table A-3 show that the dielectric properties of the rubbers are considerably impaired as a result of irradiation. Irradiation decreased the moisture resistance of the rubbers. After immersion in water, the specimens which had not been irradiated had better dielectric properties than the irradiated rubbers. The Soviets feel that the poorer dielectric properties of vulcanizates exposed to radiation are due to their increased content of polar groups, which form as a result of the radiation oxidation of the raw rubber component.

The rubbers studied were arranged by Dubrovin in the following decreasing order of radiation stability (estimated from the extent to which initial tensile strength was preserved):

ShN-40 (based on polychloroprene)

ShBM-40 (based on Buna-S plus lithium-polymerized butadiene)

NShI-35 (based on polychloroprene plus natural rubbers)

TS-35 (based on natural and sodium-polybutadiene rubbers)

TSSh-30 (based on natural and sodium-polybutadiene rubbers)

TSSh-35 (based on natural and sodium-polybutadiene rubbers).

None of these show improved properties over U. S. elastomers.

Two Soviet scientists, Taubman and Yanova, studied the role of gas formation in the degradation of polymethyl methacrylate under the action of radiation.⁽²⁶⁾ They learned that, below the softening point of the polymer, the amount of gas formed was small, but above it the gas formation was greatly accelerated. They explained this fact by the reversibility of the radiation reaction, which was shown further by the formation of the treelike crack which originates on irradiating polymers below their glass temperatures.

Kuz'minskiy and Zhuravskaya⁽²⁷⁾ discussed the resistance of rubbers to the action of ionizing radiations. At doses of $4.4 \times 10^{10} - 10^{11}$ ergs g^{-1} (C) ($5 \times 10^8 - 10^9$ roentgens), most rubbers are transformed into a brittle glasslike material. The effect depends essentially on the nature of the rubber. The different rubber types may be arranged in the following declining series: polydimethylsiloxane rubber (SKT), butadiene-nitrile (SKN-26), sodium-butadiene (SKB), vinyl-pyridine, butadiene-styrene (SKS-30), natural rubber, and isoprene rubber. Butyl rubber is the least resistant to ionization. Acrylates, chloroprene, and nitrile polymers may be recommended at doses to 8.8×10^8 ergs g^{-1} (C) (10^7 roentgens).

Vulcanizates based on butadiene-styrene copolymers retain satisfying physical-mechanical indices at doses of 8.8×10^{10} ergs g^{-1} (C) (10^9 roentgens). Heat and ionization resistance were tested simultaneously in polysilicone, urethane-isocyanate, and fluoro-elastomers. Urethane-isocyanates show good results at doses up to $8.8 \times 10^9 - 10^{10}$ ergs g^{-1} (C) ($10^8 - 10^9$ roentgens). Irradiation of sulfur vulcanizates by small doses leads to the formation of additional C-C crosslinks with increased heat resistance. The radiation resistance of synthetic rubbers is lower than that of natural rubber. Vulcanization conditions have no effect on radiation resistance. The introduction of antioxidants has a positive effect in this respect. The presence of chemically bound sulfur reduces the rate of structure formation. The use of large amounts of "heavy" fillers, like lithopore, accelerates the aging process. The brittleness and hardness induced by irradiation cannot be eliminated by means of plasticizers, like dibutyl-sebacate, dioctyl-phthalate, etc. Protective additions are aniline and benzoquinone in the case of polymethylmethacrylate, as well as acceptors for free radicals, like m-dinitrobenzene, 2,4-dinitrophenol, etc. "Modified" fillers which absorb various ingredients on their surface show good results when subjected to irradiation.

Kuz'minsky and co-workers⁽²⁸⁾ discussed results of their studies on radiation-induced polymerization of various elastomers, using gamma and X-radiations. A Co-60 source with an activity of 16,000 gram-equivalents of radium is being constructed (1958) to study the radiation effect on raw and vulcanized rubbers and other polymeric materials.

Vodop'ianov, et al.⁽²⁹⁾ reported on the effect of gamma irradiation on the dielectric properties of phenol formaldehyde plastics. When irradiation materials such as *AG-4, K-114-35, K-211-3, and FKPM-25, with 30,000 to 50,000 roentgens at 500 to 530 $r\ m^{-1}$, the loss of conductivity increases especially in K-114-35. The most important angles of loss are observed after irradiation at -60 C and under tropic conditions (AG-4). The electric strength of the plastics investigated did not change practically after gamma-radiation. Specific inductive capacitance remained the same.

RADIATION EFFECTS ON SPECIFIC POLYMERIC COMPONENTS

The radiation environment to which components may be subjected may include alpha, beta, and gamma radiations, and neutrons and protons. Neutrons are normally separated into the two categories, i. e., fast and thermal neutrons. A given component may be subjected to one or more of these types of radiation, in addition to other environments, such as heat vacuum, fuels, oils, and humidity. Hence environmental interactions may lead to failure where the device would probably not fail if exposed to a segregated environment. Therefore, selection of materials is important so that the component functions satisfactorily regardless of the environmental condition.

This section presents information on the serviceability of components in radiation and other environments. Component information is presented alphabetically.

*Specific compositions were not identified.

Adhesives

Information concerning the radiation stability of adhesives is available only for those types developed for structural applications in aircraft and missiles. These are primarily used for metal bonding, and being organic materials, are susceptible to heat and radiation damage.

Irradiation studies have been made on phenolic-epoxy, vinyl-phenolic, nylon-phenolic, epoxy, and nitrile rubber-phenolic types of adhesives. Neutron, electron, or gamma radiations cause similar damage at similar dosages.

In general it has been found that adhesives developed for high-temperature use, such as the phenolic-epoxy types, have better resistance to radiation than the thermoplastic and general-purpose types. Phenolic-epoxy adhesives, such as Shell 422 J and Narmco 25-1, have excellent radiation stability at room temperature, retaining useful strength properties to a radiation-exposure dose of 10^{11} ergs g^{-1} (C). For elevated temperatures (to 500 F), Adhesive 422 J appears to be the best material tested. It retains good shear strength when tested at 500 F after being exposed at room temperature to a radiation dose of 8.1×10^{10} ergs g^{-1} (C). A vinyl-phenolic adhesive on a glass carrier, FM-47, and a modified nylon-phenolic adhesive, Cycleweld C-6, retain good shear strength at 10^{11} ergs g^{-1} (C); however, they do not have the high-temperature characteristics of the phenolic-epoxy type. Most epoxy and nitrile rubber-phenolic adhesives show good adhesion at room temperature to 5×10^{10} ergs g^{-1} (C). Neoprene-phenolic adhesives appear to be useful to 10^{10} ergs g^{-1} (C). The rubber-phenolic adhesives are generally more flexible than the phenolic-epoxy type, but the bonded areas tend to creep when under shear stress.

In general, fillers improve the radiation stability of an adhesive, although in some cases at a sacrifice of the over-all shear strength. The curing agent and reactive diluent used in epoxy adhesives will also influence the radiation stability of the adhesive. Aromatic curing agents generally produce more-radiation-resistant compositions than do the aliphatic curing agents.

Table 9 lists the various classes of adhesives in order of their radiation stability according to shear-strength data. The known maximum operating temperatures are listed in parenthesis beside the name of the adhesive. Following is a general discussion of the various studies carried out on these materials.

Epoxy-Phenolic Adhesives

These adhesives have shown good stability after having been irradiated to a maximum dose of 8×10^{10} ergs g^{-1} (C). They were developed specifically for high-temperature applications and, therefore, also have good heat stability.

Arlook and Harvey⁽¹⁰⁾ determined tensile shear strength and bend strength on Shell epoxy-phenolic Adhesive 422 J at room temperature, 180, 260, and 500 F after irradiation at ambient temperature. Fatigue resistance was determined only at room temperature. This adhesive, also known as Hexcel 422, is provided as a support tape, the carrier being a 112 glass fabric with Volan A finish. The data from these tests are tabulated in Table A-4. Figure B-1 shows the changes in tensile shear strength and bend strength at the different temperatures after irradiation. Tests at 500 F showed that the tensile shear strength did not drop much below the original value of 1,600 psi after the

TABLE 9. RELATIVE RADIATION RESISTANCE OF STRUCTURAL ADHESIVES

I. Adhesives maintaining good strength properties after exposure to 10^{11} ergs g^{-1} (C)		
1. Epoxy-phenolic adhesives		
422 J (-65 to 600 F)		Shell Chemical Company
Narmco 2501		Narmco, Incorporated
2. Vinyl-phenolic adhesives		
FM-47 (-65 to 200 F)		Bloomington Rubber Company
3. Modified nylon-phenolic adhesives		
Cycleweld C-6		Chrysler Corporation, Cycleweld Division
II. Adhesives maintaining good strength properties after exposure to 5×10^{10} ergs g^{-1} (C)		
1. Epoxy adhesives		
Epon 828		Shell Chemical Corporation
Epon VI (-65 to 200 F)		Ditto
Epon VIII (-65 to 200 F)		"
Armstrong A-6 (-65 to 200 F)		Armstrong Products Company
2. Epoxy-Thiokol adhesives		
FA-1: Epon 828		
Thiokol LP-2		Thiokol Corporation
FA-2: Armstrong C-1		
Thiokol LP-2		Armstrong Products Company
LCA-1: Epon 828		
Thiokol LP-2		
Calcium carbonate filler		
LCA-2: Armstrong C-1		
Thiokol LP-2		
Calcium carbonate filler		
3. Nitrile rubber-phenolic adhesives		
AF-6 (-65 to 200 F)		Minnesota Mining & Manufacturing Company
EC 1245 (-65 to 300 F)		Ditto
Cycleweld A-2		Chrysler Corporation, Cycleweld Division
Metlbond 4021 (-65 to 300 F)		Narmco, Incorporated
Plastilock 620 (-65 to 300 F)		B. F. Goodrich Company
4. Nitrile rubber-epoxy-phenolic adhesives		
Bondmaster 24B		Rubber and Asbestos Corporation
III. Adhesives maintaining good strength properties after exposure to 10^{10} ergs g^{-1} (C)		
1. Neoprene-phenolic adhesives		
Cycleweld C-3 (-65 to 200 F)		Chrysler Corporation, Cycleweld Division
IV. Adhesives maintaining good strength properties after exposure to 5×10^9 ergs g^{-1} (C)		
1. Neoprene rubber-nylon-phenolic adhesives		
Metlbond MN3C (-300 to 200 F)		Narmco, Incorporated

samples had been irradiated at room temperature to a dose of between 5 and 8×10^{10} ergs g^{-1} (C). Bone strength changed less than 30 per cent at 500 F after exposure to 8×10^{10} ergs g^{-1} (C) (see Table A-4 and Figure B-2).

Fatigue strength was determined on samples after irradiation to two different doses, 7.0×10^9 ergs g^{-1} (C) (8.0×10^7 roentgens) and 6.8×10^{10} ergs g^{-1} (C) (78×10^7 roentgens). Data obtained in these tests are shown graphically in Figure B-3. Comparing these data with the control values, it is seen that there were no significant differences between the irradiated and the unirradiated specimens. In both cases, failure was adhesive rather than cohesive.

Also, DeZeih⁽³⁰⁾ irradiated test panels, using Shell Type 422 epoxy-phenolic structural adhesive, and gamma dosages ranging from 9.3×10^6 to 1.86×10^{11} ergs g^{-1} (C). These were tested for tensile shear strength at 75 F. No significant effect of radiation on the physical properties was noted.

Hexcel 422 J adhesive has also been evaluated in sandwich panel applications. Johnson and Sicilio⁽³¹⁾ at Convair bonded an aluminum skin to a glass core and determined core compression, simple beam, column creep, shear modulus, and shear strength at 260 F. There were no significant differences in properties between the irradiated and the unirradiated parts after an exposure of 2.4×10^9 ergs g^{-1} (C). Similarly, sandwich panel tests were made on an aluminum skin bonded to an aluminum core and at the same exposure. No significant differences were noted in properties of these parts (see Table A-5). Lap-shear tests at room temperature and 260 F showed no change in either 2024-T3 clad aluminum bonded to itself or magnesium to itself, after an exposure to 2.4×10^9 ergs g^{-1} (C). (See Table A-9.)

Lap-shear strengths were also determined after test samples were immersed in 3 per cent salt water, tap water, anti-icing fluids, hydraulic oil, JP-4 fuel, and hydrocarbon Type III fuel after irradiation. Again, there was no change in shear strength after exposure (see Table A-9).

Vinyl-Phenolic Adhesives

Two polyvinyl butyral-phenolic adhesives, FM-47 Tape and Cycleweld 55-9, were examined for radiation stability. FM-47 is a supported tape, the carrier being 4-mil-thick 191 lena-weave glass fabric. Cycleweld is a liquid adhesive which does not contain a filler. Test data show that the radiation stability of FM-47 is much better than that of Cycleweld 55-9, and that the use of glass tape improves its stability. FM-47 appears to be satisfactory for service to 10^{11} ergs g^{-1} (C).

According to the results of Arlook and Harvey⁽¹⁰⁾, FM-47 film, when tested at room temperature, retained 90 per cent of the room-temperature control tensile-shear strength up to the maximum radiation dose received, 7×10^{10} ergs g^{-1} (C). At a temperature of 180 F, it retained 64 per cent of the 180 F control strength at a dose of 8.6×10^{10} ergs g^{-1} (C). When tested at 260 F, it retained 83 per cent of the 260 F control strength. The tensile-shear values after an irradiation dose of approximately 8×10^9 ergs g^{-1} (C) were taken as the controls for the tests at elevated temperatures. All irradiations were at ambient temperature (approximately 74 F). The tensile-shear, bend-strength, and fatigue-test data for this adhesive are listed in Table A-6 and Figures B-4 through B-6. At 260 F, the shear strength had decreased considerably, although it was not affected to any extent by increasing radiation doses.

Mixer⁽³²⁾ irradiated FM-47 using gamma and beta irradiation. He found that the per cent change in tensile-shear strength was similar, providing the absorbed energy was similar. He also noted that the failure was adhesive rather than cohesive. Test data are given in Table A-7.

Cycleweld 55-9 increases slightly in tensile-shear strength to a radiation dose of 7.2×10^9 ergs g^{-1} (C), but, above this dose, both its tensile-shear strength and bend strength decrease rapidly. (10) When tested at elevated temperatures the change was not very great, but the control values decreased greatly, so that actual tensile-shear and bend-strength values are approximately the same as those for the room temperature tests for radiation doses above 2.4×10^{10} ergs g^{-1} (C). Test data for Cycleweld 55-9 are given in Table A-8 and Figures B-7 through B-9.

Modified Nylon-Phenolic Adhesives

Cycleweld C-6 was the only adhesive of this class tested. (10) For room-temperature applications this adhesive appears to have excellent radiation stability. Its tensile-shear strength increased from 2,180 psi for the unirradiated material to 2,510 at a dose of 9.2×10^{10} ergs g^{-1} (C). However, at 180 F, tensile-shear properties were less than 900 psi, and dropped to 270 psi at 9.2×10^{10} ergs g^{-1} (C) exposure dose. Bend strength also decreased rapidly after a dose of 2.4×10^{10} ergs g^{-1} (C) when tested at elevated temperatures. These data are shown in Table A-10 and Figures B-10 through B-12.

Epoxy Adhesives

Several factors appear to affect the radiation stability of epoxy resins and no doubt influence the radiation stability of epoxy-based adhesives. The structure of the polymer, the curing agent used, the presence of a filler, and the reactive diluent all influence the stability of epoxy resins and adhesives. In general, the greater the aromatic content, the greater the stability of the polymer. Thus, aromatic curing agents provide greater radiation stability than do aliphatic curing agents. A polymer based on epoxy resins having a greater number of aromatic groups is generally more stable than one based on a structure having fewer phenyl groups.

Mixer⁽³³⁾ studied the radiation stability of three epoxy systems, including DEBA (a diglycidyl ether of Bisphenol-A), Epon 1001 (a longer chain Bisphenol-A diglycidyl ether), and Epon X-131 [containing tetraglycidyl ether of tetrakis (hydroxyphenyl) ethane]. These resins were cured with primary aliphatic, secondary aliphatic, and primary aromatic amines. He found that Epon X-131 was the most radiation resistant of the three epoxy resins when aromatic amines were used as curing agents. DEBA was the least radiation resistant. He found that (1) the aromatic amine product was far more stable than aliphatic amine products; (2) chain cleavage of the epoxy resins was in the aliphatic portion, i. e., in the glycidyl group rather than in the aromatic part of the molecule; and (3) the predominant effect of irradiation on epoxy polymers was crosslinking.

The filler in epoxy resins improves the radiation stability to some extent. (34) A comparison of unfilled Epon 828 and an epoxy filled with calcium carbonate (P-11 in Table A-11 shows the filled resin to be more resistant to radiation than Epon 828, although the latter had higher original shear-strength values.

In addition to those already mentioned, other epoxy adhesives which have been investigated include Epon VI, (35) Epon VIII, (10, 32) and Cycleweld C-14. (10) Epon VI and Epon VIII were used with Shell Curing Agent A, an alkyl amine (an aliphatic compound). Epon 828 and P-11 mentioned above were cured with piperidine (an aromatic compound). The chemical composition of the other curing agents was not disclosed. The effect of radiation on tensile-shear strength, bend strength, per cent flow under load, and fatigue for these adhesives is shown in Tables A-12 through A-15, and Figures B-13 through B-17. Test procedures and conditions were not the same in all cases and, therefore, the data for these epoxy adhesives are not always comparable. However, in general it appears that the various epoxy resins tested are about equivalent in radiation stability at room temperature.

Only two of these adhesives, Epon VIII and Cycleweld C-14, were tested at elevated temperatures. Irradiation in all cases was at room temperature. An examination of Table A-13 and Figures B-13 and B-14 shows that Epon VIII, when irradiated to 10^{10} ergs g^{-1} (C), has about the same radiation stability in tensile shear when tested at 180 F as it does when tested at room temperature. Above that dose, the rate of change is greater for the sample tested at 180 F. At 260 F, the strength is considerably lower, although the changes due to radiation are similar to those shown by samples tested at room temperature. The bend strength is lower at the higher temperatures but the changes due to increasing radiation are similar at the three temperatures.

Cycleweld C-14 behaves differently from Epon VIII (see Table A-15 and Figures B-16 and B-17). At room temperature, tensile-shear strength decreases only about 8 per cent at a dose of 2.9×10^{10} ergs g^{-1} (C). Above that dose, tensile-shear strength decreases rapidly. At 180 F and 260 F, tensile-shear strength of samples irradiated to 8.7×10^9 ergs g^{-1} (C) is less than 200 psi. This appears to be due to the effect of heat rather than to the effect of radiation. The decrease due to radiation is almost nil. The same holds true for the bend strength of this adhesive. Cycleweld C-14 is a modified epoxy and it would appear that the modifier decreases its heat stability.

Epoxy-Thiokol Adhesives

Thiokol (polysulfide rubber) is added to epoxy resins to give more flexibility and to improve adhesion. Four epoxy-Thiokol adhesives were examined for radiation stability⁽³⁴⁾. Two were based on Epon 828 and two on an Armstrong epoxy resin, C-1. One of each of these contained calcium carbonate as a filler. Data for these adhesives are given in Table A-16. An examination of these data shows that the addition of neither Thiokol nor the filler improved the tensile properties of the epoxy adhesives to any appreciable extent. In most cases there was a degradation of tensile strength.

At the highest radiation dose, 8.5×10^{10} ergs g^{-1} (C), the shear strengths of all four compositions as well as of the two epoxy resins appeared to drop to about the same value. These adhesives followed the same general trend of the epoxy adhesives in that they showed little damage at 10^{10} ergs g^{-1} (C), but significant loss in strength at 8.5×10^{10} ergs g^{-1} (C). However, the tensile-shear strength of some of them increased greatly at low radiation doses.

Nitrile-Phenolic Adhesives

Rubber-based adhesives have given excellent bonding strengths and are often used where greater flexibility is required than is generally obtained from phenolic- or

epoxy-type adhesives. Some of these adhesives have very high tensile-shear strengths, combined with good radiation stability at room temperature. Adhesives in this group that have been tested include Scotchweld AF-6⁽¹⁰⁾, EC-1245⁽³⁵⁾, Metlbond 4021⁽³⁵⁾, Cycleweld A-Z⁽¹⁰⁾, and Plastilock 620⁽³¹⁾. Data for these adhesives are given in Tables A-17 through A-20 and Figures B-18 through B-23.

These adhesives generally lose their high tensile strengths at elevated temperatures, limiting their applications to temperatures below 250 F. Their radiation stability is good at higher temperatures, since irradiation appears to improve their adhesive strength. Only lowering of the tensile strength appears to be due entirely to heat. It should also be pointed out that, although tensile strength is decreased at elevated temperatures, there remains sufficient strength for many applications.

Plastilock 620, manufactured by the Goodrich Rubber Company, was tested as an adhesive for bonding 2024-T3 clad aluminum, 7075-T6 unclad aluminum, and magnesium and for bonding magnesium to 2024-T3 clad aluminum.⁽³¹⁾ The only change in shear strength due to irradiation occurred with the magnesium-to-2024-T3 clad aluminum specimens. These showed a slight decrease in shear strength after a dose of 2.4×10^9 ergs g^{-1} (C). Tests were made at room temperature and at 260 F, but irradiation was at room temperature. Samples were immersed in 4 per cent salt-water solution, tap water, anti-icing fluid, hydraulic oil, JP-4 fuel, and hydrocarbon Type III fuel after irradiation, with no change in shear strength. Data are given in Table A-17. Plastilock 620 was not tested above 2.4×10^9 ergs g^{-1} (C).

Adhesive AF-6 had an original shear strength of 2,900 psi which was somewhat lower than that for other adhesives in this class (see Table A-18 and Figures B-18 through B-20). However, when tested at 260 F after being irradiated at room temperature to a dose of 5.5×10^{10} ergs g^{-1} (C), the adhesive retained approximately one-third of its strength, decreasing to 1,030 psi. Another adhesive, Cycleweld A-Z, retained some strength at 500 F. The original room-temperature tensile-shear strength was 2,030 psi (see Table A-19 and Figures B-21 through B-23). After Cycleweld A-Z was irradiated to 7.1×10^{10} ergs g^{-1} (C), tensile-shear strength at 500 F was 370 psi. Adhesives EC-1245 and Metlbond 4021 had excellent original tensile strengths. They retained tensile strength above 4,000 psi when irradiated to 1.7×10^{10} ergs g^{-1} (C). EC-1245 lost this strength very rapidly at exposures above this dose. The Metlbond 4021 was not irradiated to a high dose, but would probably behave similarly. (See data in Table A-20.) These adhesives were not irradiated at elevated temperatures, so it is not possible to determine their effectiveness for applications requiring good adhesion while being subjected to radiation at elevated temperatures.

Nitrile-Epoxy-Phenolic Adhesives

This class is a modification of the preceding class of adhesives. Bondmaster 24B, manufactured by Rubber and Asbestos Corporation, was tested for tensile-shear strength after irradiation.⁽³⁵⁾ It was found to be similar in tensile-shear strength and radiation stability to the nitrile-phenolic adhesives discussed above, being stable to about 5×10^{10} ergs g^{-1} (C). The data are shown in Table A-21.

Neoprene-Phenolic Adhesives

A neoprene-phenolic rubber adhesive, Cycleweld C-3⁽¹⁰⁾, decreased on irradiation at a fairly uniform rate. At a radiation dose of 10^{10} ergs g^{-1} (C), its tensile-shear

strength had decreased by about 38 per cent and bend strength by 54 per cent. The data are shown in Table A-22 and Figures B-24 and B-25. The changes due to irradiation appeared to be similar when the material was tested at the higher temperatures. It is not recommended that this adhesive be used beyond a radiation dose of 10^{10} ergs g^{-1} (C).

Neoprene-Nylon-Phenolic Adhesives

Metlbond MN3C (Narmco, Inc.), supplied both as a liquid and as a tape with a nylon fabric carrier, was examined for tensile-shear strength after irradiation to approximately 10^{10} ergs g^{-1} (C).⁽³⁵⁾ Data are shown in Table A-23. Although its original shear strength is slightly higher than that of a neoprene-phenolic its radiation stability appears to be poorer than that of other rubber-phenolic types. Shear strength was the only property reported for this adhesive. The adhesive possibly may be used for some applications at radiation doses of 5×10^9 ergs g^{-1} (C) to 10^{10} ergs g^{-1} (C). Lap-shear test specimens made using 2024-T3 clad aluminum, 7075-T6 unclad aluminum, and magnesium were irradiated in air to 2.4×10^9 ergs g^{-1} (C) and then tested at room temperature and 180 F.⁽³¹⁾ There was no major change in the shear strength at the test temperatures. The data are given in Table A-24.

Coatings

Coatings generally considered for present and future use in the aviation industry are based on the following materials: phenolics, furanes, alkyds, silicone alkyds, vinyls, nitrocellulose, neoprene, styrene-butadiene, and epoxy.⁽³⁶⁾ Coatings and paints prepared from all these resins except polyvinyl chloride and nitrocellulose appear to be satisfactory for use after exposure to 8.7×10^{10} ergs g^{-1} (C) (1×10^9 roentgens). The vinyl and nitrocellulose resins are least resistant to radiation and are only satisfactory to the 10^{10} ergs g^{-1} (C) exposure. Exposure up to 500 F has little effect on a phenolic coating at 8.7×10^{10} ergs g^{-1} (C).

Additives such as pigments, plasticizers, and other coating ingredients, as well as the type of surface on which the coating is applied, influence the radiation stability of the coating. Coatings which are highly pigmented are generally more resistant to radiation than similar gloss coatings containing lesser amounts of pigments. Carbon black inhibits damage due to radiation, while toluidine red has little effect. Titanium dioxide appears to accelerate radiation damage. Coating systems, especially lacquers, employing wash primer become embrittled, and poor adhesion between the coating system and the substrate occurs. Degradation begins at lower doses for coatings applied to steel as compared with coatings applied to asphalt. Applied coatings, irradiated while they are wet, do not have the stability observed for coatings which have been dried. Studies show that Alkaloy (furan base) and Epon-395 (epoxy base) coatings have good chemical resistance after exposure to approximately 8.7×10^{10} ergs g^{-1} (C) (10^9 roentgens). Amphesive-801, a modified phenolic, loses its resistance to sodium hydroxide and the organic solvent, hexone (methyl isobutyl ketone), as a result of irradiation. Epon 1001 also loses its resistance to hexone when irradiated. Epon-395 becomes resistant to sulfuric and hydrochloric acids as a result of gamma irradiation. The approximate radiation resistance for selected coatings is shown in Table 10.

TABLE 10. APPROXIMATE LIMITS OF RADIATION RESISTANCE OF SELECTED ORGANIC COATINGS

Coating	Approximate Radiation Resistance	
	Ergs g ⁻¹ (C)	Roentgens
Phenolic	>4.4 x 10 ¹¹	>5 x 10 ⁹
Silicone-alkyd	8.8 x 10 ¹⁰ - 4.4 x 10 ¹¹	1 - 5 x 10 ⁹
Alkyd enamels 40% phthalic anhydride MIL-D-5557	8.8 x 10 ¹⁰ - 4.4 x 10 ¹¹	1 - 5 x 10 ⁹
32% phthalic anhydride MIL-E-7729	6.1 x 10 ¹⁰ - 8.8 x 10 ¹⁰	7 - 10 x 10 ⁸
Epoxy	4.4 x 10 ¹⁰ - 8.8 x 10 ¹⁰	5 - 10 x 10 ⁸
Fluorinated vinyl	4.4 x 10 ¹⁰ - 8.8 x 10 ¹⁰	5 - 10 x 10 ⁸
Nitrocellulose lacquers	4.4 x 10 ¹⁰ - 6.1 x 10 ¹⁰	5 - 7 x 10 ⁸

The resistance of organic coatings to radiation can be predicted to some degree from the data available on polymers and plastics. However, because of the complicating factors introduced by pigments, plasticizers, and other coating ingredients, exact predictions of a coating's resistance to radiation can be obtained only by laboratory or field testing.

Twenty different experimental and specification coating systems designated for use on military aircraft were irradiated at the Naval Air Material Center in the Aeronautical Materials Laboratory cobalt-60 unit. (37) Table A-25 identifies these materials and lists the effects of radiation on the systems at four different doses. Periodic evaluation of the systems after irradiation indicated the following results:

- (1) Most of the topcoats darkened after exposure to only 6.7×10^9 ergs g⁻¹ (C) (8.0×10^7 roentgens). High loadings with extender pigment appear to contribute to the color change, since in some cases the nonspecular coatings which contained large amounts of extenders exhibited some color change, whereas no color changes were evident in their glossy counterparts.
- (2) Nonspecular coatings which contained large amounts of extender pigments were generally more resistant to radiation, with respect to softening and embrittlement, than similar gloss coatings containing smaller amounts of pigment.
- (3) When coating systems, especially lacquers, employing primers were irradiated, the entire system generally became embrittled and poor adhesion developed between the coating system and the metal substrate.

- (4) No differences were noted between the anodized and alodine-treated aluminum surfaces with respect to film properties of the organic coatings.
- (5) The topcoats least affected were the white MIL-E-5556 enamel, the amber MIL-R-3043 permanent resin coating, an experimental white silicone-alkyd, an experimental white all-silicone, and a proprietary white amine-catalyzed epon.

Screening studies were performed at Oak Ridge National Laboratory on 23 mounted coatings and on 8 unmounted coatings⁽³⁸⁾ at radiation levels up to 10^{11} ergs g^{-1} (C). These materials are identified in Table A-26. Of the 23 mounted coatings tested, only 4 polymer-base types did not fail at the maximum dose used. These were the furanes, the epoxies, the silicone-alkyds, and one modified phenolic specimen (Coatings 1, 6, 7, 9, 11, 14, 15, and 21 in Table A-27). Table A-28 shows the results of chemical stability and decontamination tests. The furane-base and epoxy-base coatings (Coatings 1 and 14, respectively) showed excellent chemical resistance and decontaminability. Two other coatings of similar polymer base (Coatings 11 and 15) both lacked solvent resistance after irradiation. Table A-29 lists the effects of radiation on the unmounted coatings. Of these GE Cocoon, a vinyl polymer was best. It retained its flexibility but the surfaces became tacky.

Minden⁽³⁹⁾ found that an epoxy resin primer showed very good radiation resistance when irradiated for 20 hours at 500 kw at 300 F. The total exposure was 3.2×10^{14} n cm^{-2} ($E > 2.9$ Mev) and 4.1×10^9 ergs g^{-1} (C). Baked panels gave the optimum radiation resistance and were resistant to JP-4 fuel.

Horrocks at ASD⁽⁴⁰⁾ noticed a striking difference when different pigments were used with the same resin. White titanium dioxide appears to accelerate damage in nitrocellulose lacquers. Toluidine-red has little effect, whereas carbon black inhibits radiation damage. A valid comparison of various coating systems that have been exposed to gamma radiation can be made only if the same type of pigmentation is used throughout. This conclusion is similar to that found for polyethylene.

Horrocks also reported results of tests performed on six organic coatings: phenolic, silicone-alkyd enamel, alkyd enamel, epoxy, fluorinated vinyl (copolymer of trifluorochloroethylene and vinylidene fluoride), and nitrocellulose lacquer. Two of these, nitrocellulose lacquers and alkyd enamels, are widely used on today's aircraft. The remainder either are used to a limited extent or are being contemplated for future applications. All of these coating systems were applied to AZ31 magnesium alloy treated with a Dow No. 7 chemical-conversion coating.

The coatings were evaluated at three different radiation levels: 8.8×10^9 , 8.8×10^{10} , and 4.4×10^{11} ergs g^{-1} (C) (1×10^8 , 1×10^9 , and 5×10^9 roentgens). Controls were run on all coatings. Some coatings were exposed for 50 hours at 250 and 500 F following radiation exposure to measure the combined effects of radiation and heat. The results of these tests are presented in Table 11.

In general, irradiated phenolic coatings baked 50 hours at 500 F retain their properties better than any of the other coatings evaluated. The surface appearance of test panels remained unchanged after exposure. In addition to maintaining good abrasion resistance and adhesion, the coatings were little affected by exposure to 100 per cent relative humidity at 120 F for 28 days.

TABLE 11. PROPERTIES OF ORGANIC COATINGS AFTER EXPOSURE TO GAMMA RADIATION^(a)

Coating Type and Co-2	Base Temp. (50 in F)	Radiation Exposure, Mr	Total Absorption, cycles in inches	Flexibility ^(b)	Adhesion ^(c)	Fractional Viscosity ^(d)	Exposure, Days	Extent of Blistering	Deflection, % ^(e)		
									400 Mr	500 Mr	750 Mr
Phenolic, hard ^(f)	None	0	-	-	-	-	-	-	7	5	8
											25
	250	0	100	Flexed	Good	0.02	4-12	Many	7	5	7
		10	100	Flexed	Good	0.05	12	Many	7	5	23
	500	0	100	Cracked	Good	0.09	28	Many	10	9	8
		10	100	Cracked	Very good	0.05	28	None	10	9	8
	None	0	200	Good	Good	0.08	28	None	45	90	90
		10	200	St cracked	Good	0.08	28	None	45	30	90
		10	500	St cracked	Good	0.01	28	None	45	30	90
		10	65	St cracked	Fin.	0.70	28	None	42	75	84
	500	0	100	Cracked	Fin.	None	28	None	20	28	37
		10	100	St cracked	Good	None	28	None	22	31	40
		10	210	Good	Good	None	28	None	21	30	41
		10	335	St cracked	Fin.	None	5	None	13	15	25
	None	0	50	St cracked	Fin.	0.55	4	Many	4	4	4
		10	50	Good	Fin.	0.50	4	Many	4	4	4
	None	0	100	Cracked	Fin.	0.54	4	Many	5	5	17
		10	100	Cracked	Fin.	0.55	4-5	Many	5	5	17
	None	0	100	Cracked	Fin.	0.25	4	Many	42	34	52
		10	200	Cracked	Fin.	0.75	4-5	Many	37	73	81
	None	0	100	Good	Good	0.04	28	None	17	15	13
		10	100	Cracked	Fin.	0.01	12	Slight	15	15	13
		10	100	Cracked	Fin.	0.54	4-10	Many	11	14	17
	250	0	500	Good	Good	0.02	28	Fin.	15	15	13
		10	500	Cracked	Good	0.20	12-18	Slight	12	13	12
		10	500	Flexed	Fin.	0.55	4	Many	8	9	10
	None	0	50	Good	Good	0.04	25	None	17	15	13
		10	50	Good	Fin.	0.01	12	Many	15	15	13
		10	50	Good	Fin.	0.04	4-12	Many small	11	14	17
	250	0	200	Good	Good	0.02	28	Slight	15	15	13
		10	200	Good	Good	0.02	28	Slight	15	15	13
		10	200	Flexed	Fin.	0.55	4	Many	8	9	10
	None	0	100	Good	Good	0.04	4-5	Many small	45	73	77
		10	100	Flexed	Fin.	0.25	28	Slight	24	52	68
	None	0	70	Good	Good	0.05	28	None	5	5	13
		10	100	Flexed	Fin.	0.03	28	None	5	5	12
	None	0	100	Good	Good	0.50	5	Many small	5	4	4
		10	100	Good	Good	0.33	28	Many small	5	4	4

^a Coatings applied to A231 impregnated alloy treated with Bar No. 7 chemical conversion coating.^b Determined by bending 1/2-in. panel over 3/4-in. mandrel.^c Tested with Aero Mac-Fab.^d Fraction of vapors removed when a gelable latex is cast with an Aero Mac-Fab.^e Exposed to air and relative humidity of 100%.^f General Electric recording spectrofluorometer.^(a) MIL-4-2340.^(b) MIL-4-2552. Applied over zinc chromate primer, MIL-P-4882, Type I.^(c) MIL-4-2728. Applied over zinc chromate primer, MIL-P-4882, Type I.^(d) MIL-4-2552.^(e) MIL-4-2728. Applied over zinc chromate primer, MIL-P-4882, Type I.

Except for some crosslinking, unbaked silicone-alkyd enamels appear to be little affected by a radiation exposure of 8.8×10^{10} ergs g^{-1} (C) (1×10^9 roentgens). However, a radiation exposure of 4.4×10^{11} ergs g^{-1} (C) (5×10^9 roentgens) produces crosslinking and slightly degrades the unbaked coating.

Silicone-alkyd coatings not exposed to radiation but heated 50 hours at 500 F become completely discolored. These coatings experienced partial destruction of the resin by oxidation. However, there is some evidence that radiation of 8.8×10^9 and 8.8×10^{10} ergs g^{-1} (C) (1×10^8 and 1×10^9 roentgens) rearranges the silicone-alkyd resin and provides it with more heat resistance. Coatings exposed to these radiation levels and to heat exhibit better film condition, abrasion resistance, and flexibility than do unexposed coatings. Exposure to 4.4×10^{11} ergs g^{-1} (C) (5×10^9 roentgens), however, produces oxidation and crosslinking of the resin, and causes the coating to become powdery and brittle.

After exposure to 8.8×10^{10} ergs g^{-1} (C) (1×10^9 roentgens), both red and white 32 per cent phthalic anhydride alkyd enamels become embrittled and change color. This embrittlement is probably caused by oxidation and crosslinking at the double bonds. Also, after exposure the white enamel exhibits a large increase in abrasion resistance and a large decrease in adhesion. The red enamel suffers only a slight decrease in adhesion after exposure.

In contrast to the red and white alkyd enamels, the black 32 per cent phthalic anhydride alkyd enamel softens when exposed to 8.8×10^{10} ergs g^{-1} (C) (1×10^9 roentgens). This increased softness manifests itself by decreased adhesion and abrasion resistance, and by greater flexibility.

The properties of the epoxy coatings are severely degraded by radiation exposure with one exception, i. e., an increase in the abrasion resistance of unbaked coatings. The poor resistance of coatings to radiation is probably due to excessive crosslinking and/or degradation of the aliphatic portions of the chains. Also, the metal coating bond seems to be preferentially attacked, as evidenced by the marked decrease in adhesion after irradiation.

Fluorinated vinyl coatings are usually fused to provide good adhesion. Exposure of unfused coatings to 8.8×10^{10} ergs g^{-1} (C) (1×10^9 roentgens) results in improved adhesion and abrasion resistance. However, increasing radiation produces crosslinking and bond-breaking degradation, and causes the coating to lose its good cohesion and corrosion resistance. Increasing the radiation level to 4.4×10^{11} ergs g^{-1} (C) (5×10^9 roentgens) causes the unfused coating to blister and flake. Coatings heated at 250 F show similar results except that adhesion starts to decrease at a lower radiation level; the coating begins to peel and flake at 8.8×10^{10} ergs g^{-1} (C) (1×10^9 roentgens).

Extensive degradation of all physical and mechanical properties is exhibited by white nitrocellulose lacquers after exposure to 8.8×10^{10} ergs g^{-1} (C) (1×10^9 roentgens). The coatings become quite porous and their over-all condition is poor. The same exposure is not as damaging to red lacquers; these lacquers become brittle and non-porous after exposure but their adhesion increases.

With the exception of surface damage, the properties of the black lacquers are improved after exposure; such coatings exhibit a significant increase in toughness and adhesion.

In another study⁽⁴¹⁾, Horrocks used a white, highly pigmented, porous silicone-alkyd (Plaskon ST-873 resin). The high pigmentation caused it to be relatively hard and brittle. The excellent humidity resistance was due to the porosity, which permits free passage of water vapor. The unbaked sample was little affected by radiation to 8.8×10^9 ergs g^{-1} (C) (1×10^8 roentgens). This exposure produced slightly less flexibility but better adhesion. Exposure to 8.8×10^{10} ergs g^{-1} (C) (1×10^9 roentgens) greatly increased adhesion and abrasion resistance and slightly decreased reflectance. Further exposure to 4.4×10^{11} ergs g^{-1} (C) (5×10^9 roentgens) gave a considerable decrease in reflectance, adhesion, and film condition, and a further increase in abrasion resistance.

Baking alone had a considerable effect on the sample. The coating had begun to char, cracked in the flexibility test, and had less abrasion resistance. Radiation of 8.8×10^9 and 8.8×10^{10} ergs g^{-1} (C) (1×10^8 and 1×10^9 roentgens) improved abrasion resistance, flexibility, and condition of the film. Further radiation to 4.4×10^{11} ergs g^{-1} (C) (5×10^9 roentgens) decreased these properties.

The author explains that the increase of apparent adhesion and abrasion resistance for the unbaked samples exposed to 1×10^8 and 1×10^9 roentgens indicates embrittlement caused by crosslinking and an increase in actual adhesion due to more bonding with the surface. Exposure to 4.4×10^{11} ergs g^{-1} (C) (5×10^9 roentgens) further increased embrittlement and degraded the coating; however, there was an additional increase in abrasion resistance.

The change in properties observed in the baked samples indicates that the coating was stabilized by radiation. This may have occurred because radiation causes the most oxygen-labile groups to rearrange, giving the coating more oxidation resistance. At doses of 4.4×10^{11} ergs g^{-1} (C) (5×10^9 roentgens) the coating became brittle and powdery.

Electrical Insulation

For most insulators, permanent changes in electrical properties with irradiation are minor, and the life of the insulation depends upon its resistance to mechanical damage. Most plastics used for insulators harden and eventually become brittle in a radiation field. This results in peeling and chipping, especially under flexure. Inorganic insulators, such as ceramics, glass, and mica, and organic-inorganic combinations, such as mica and glass used with silicone or phenolic varnishes, can be used successfully in high-temperature and high-radiation environments. Most of the plastics can be used at medium radiation intensities if their temperature limits are not exceeded. Teflon, however, has poor radiation resistance. Twenty-five per cent damage is accrued at 3.4×10^6 ergs g^{-1} (C); however, it has been reported useable up to 4.4×10^9 when immersed in oil.⁽⁴²⁾

The insulation resistance of organic materials used in cables, wire insulation, or seals may decrease by a factor of 10^3 to 10^4 for gamma irradiation rates of 10^4 to 10^6 r/hr. This is generally a rate effect, but permanent damage can occur for large total doses. This effect could cause difficulty in high-impedance circuits.⁽⁴³⁾

Blasi⁽²²⁾ carried out studies to determine what changes, if any, take place in the dielectric properties of dielectric materials while they are exposed to nuclear

irradiation. Considerable data have been published on the subject of permanent damage sustained by materials both in electrical and physical properties, based on measurements made before and after irradiation. Very little information is available on transient electrical characteristics exhibited within an actual nuclear environment. Teflon and polystyrene, Rexolite 1422, were used in these studies. The samples were measured prior to irradiation to establish reference values. Tests were conducted immediately upon introduction of the radioactive source and regularly during the period of experimentation. Finally, the samples were evaluated at intervals up to 10 days after their removal from the radioactive environment.

The Teflon samples were exposed to irradiation varying from 3.6×10^5 roentgens per hour to 2.5×10^3 r/hr as a function of its distance from the source. Integrated dose was calculated to vary from 1.1×10^6 r to 8.0×10^4 r. The polystyrene sample was exposed to an integrated dose varying from 4.2×10^7 to 2.9×10^5 r. Within the limits of the experiments performed, neither Teflon nor the polystyrene showed any significant change in dielectric properties.

It would appear that, as far as total dose is concerned, most common dielectrics could be used safely in a space vehicle subjected to natural radiation, but that each proposed material should be considered carefully for transient effects before actual selection is made.

Irradiation ionizes silicone dielectrics causing rearrangement of the chemical structure and the product of impurities. (44) The rearrangement causes major effects on the physical properties. The rearrangement and the impurities produced have significant effects on some of the dielectric properties. Since some of the impurities are transitory, some of the effects are also transitory, while others are permanent. These transitory effects in some silicone dielectrics are often larger than the permanent effects and occur during, or immediately after irradiation. The transitory effects may limit the performance of silicone fluids as dielectrics during radiation exposure.

In general, the physical properties of silicone fluids, compounds, elastomers, and resins are damaged by irradiation before the essential dielectric properties are significantly and permanently affected. Therefore, the effects of irradiation on the physical properties are the primary factors in limiting the performance of silicone dielectrics after radiation exposure.

Elastomers

Irradiation doses of less than 2×10^8 ergs g^{-1} (C) (200 megarads) have little significant effect on the dielectric properties of silicone elastomers. The physical properties of silicone elastomers, however, are affected by relatively low doses. After a dose of 10^8 ergs g^{-1} (C) (100 megarads), the flexibility of the elastomer is adversely affected. For those numerous applications in electrical and electronic apparatus where extreme flexibility is not required once the elastomer is in place, silicones may be suitable for doses of 2×10^8 to 5×10^8 ergs g^{-1} (C) (200 to 500 megarads). Because of its heat and radiation resistance, silicone rubber is being specified for control and power cable used with atomic equipment. (45)

Christensen of Dow Corning Corporation reports that irradiation often produces the same gross effects on silicone insulation as does thermal aging.⁽⁴⁶⁾ The result is that thermal aging and irradiation are additive to a certain degree. He found that silicone resins used to bind and impregnate insulating systems seem to be the most radiation resistant of all silicone insulating materials. There are few significant effects on either the physical or dielectric properties at doses to 9.1×10^{10} ergs g^{-1} (C) (1,000 megarads). With proper filler, silicone resins are satisfactory to 10^{11} ergs g^{-1} (C). Dielectric properties are only slightly lowered at the latter exposure.

Currin and Smith⁽⁴⁷⁾ have studied the effect of high temperature and nuclear radiation on silicone insulation systems. These tests were made on random-wound equipment, form-wound equipment, wire and cable, and a complete motor. The silicone insulation systems and constructions are identified in Table A-30. Values of insulation resistance for Systems A, B, C, and D are shown in Table A-31 for exposure to radiation at 200 C and in Table A-32 for exposure to radiation alone. Tables A-33 and A-34 show the effects of gamma radiation at room temperature and 200 C, respectively, on silicone-rubber formette insulation systems.

Results of tests on silicone rubber used as wire and cable insulation show that this material has some applications at 25 C for doses of 4.5×10^9 to 1.8×10^{10} ergs g^{-1} (C) (50 to 200 megarads). At 200 C, the life is estimated to be between 4.5×10^8 and 3.6×10^9 ergs g^{-1} (C) (5 and 40 megarads), depending upon the mechanical requirements of the application, the type of silicone rubber used, and the construction of the wire. Where high voltage, moisture, and flexing of the insulation are absent, life may approach 100 megarads at 200 C.

A silicone-insulated motor operated satisfactorily for over 4,000 hours at 200 C in the gamma-radiation field. The motor winding nearest the radiation source received about 7.7×10^9 ergs g^{-1} (C) (85 megarads). Without irradiation this insulation system has a life greater than 20 years at 200 C. Currin⁽⁴⁷⁾ states that experimental silicone-rubber formulations are being developed that appear to be more resistant to radiation than those evaluated. Preliminary tests indicate that these new materials are serviceable after exposure to high temperatures and several hundred megarads. These radiation-resistant silicone rubbers are not yet available commercially, but design engineers can anticipate their availability for future applications.

Further proof of the reliability of silicone materials used in insulation is given by Javitz.⁽⁴⁸⁾ He reports the findings of Currin and Dexter, Dow Corning Corporation, in studies of dielectric properties of silicones during and after irradiation. Samples were exposed in air at 25 C to a multikilocurie cobalt-60 source emitting gamma rays to approximately 1.25-Mev energy. Duty cycle was about 20 hours "On" and 4 hours "Off" per day. Doses of 9.1×10^9 and 4.5×10^{10} ergs g^{-1} (C) (100 and 500 megarads) were supplied. Table A-35 shows the dielectric properties of silicone fluids, elastomers, and resins after irradiation compared with those prior to irradiation. These resins show greater resistance to radiation effects than any other types of silicones. Dielectric properties of the filled, solventless, silicone resin and a modified silicone wire enamel were essentially unaffected by 9.1×10^{10} ergs g^{-1} (C) (1,000 megarads).

A small linear decrease in dielectric constant and dissipation factor was observed with the silicone elastomers, particularly at frequencies under 100 cycles per second. As would be expected, the major effects on elastomers were physical; they increased in hardness and lost flexibility. Silicone elastomers may be suitable in applications where

a high degree of flexibility is not required at doses to 4.5×10^{10} ergs g^{-1} (C) (500 megarads). It is possible that reinforcement with glass cloth may extend life.

In the same article⁽⁴⁸⁾, Javitz reports that the dielectric constants of silicone materials decrease slightly during radiation in a field equivalent to dose rates greater than 1.8×10^6 ergs g^{-1} (C) (0.02 megarad) hr^{-1} . The dissipation factor increases considerably when a strong radiation field is applied while resistivities decrease. Data in Table A-36 indicate that the silicones are suitable as dielectrics when the radiation dose rate is kept at 9.1×10^6 ergs g^{-1} (C) (0.1 megarad) hr^{-1} .

The General Electric Company, Cincinnati, studied the serviceability of commercially available silicone-rubber-insulated cable of the types used in jet engines.⁽⁴⁹⁾ Serviceability was judged by flexing the cable after irradiation. These materials were scored excellent, good, fair, and poor. Good materials could be flexed 180 degrees ten to twelve times without failure, while poor materials could be flexed only two or three times without failure. Table A-37 lists the results of preliminary irradiation of electrical-cable insulations and Table A-38 identifies the materials tested.

Neoprene, SBR, and silicone elastomers have been evaluated for use as electrical insulation.⁽⁵⁰⁾ The neoprene and SBR insulation compounds became relatively hard and lost their flexibility at about 10^{10} ergs g^{-1} absorbed dose (100 megarads). Electrical properties for these compositions were not determined after irradiation.

Some combined environmental tests on SBR rubber have been made. An SBR wire insulation was irradiated at room temperature and at 158 F. (11, 51) The irradiated samples were then tested at these same temperatures. These data are summarized in Table A-39. For comparative purposes, the effect of heat aging without irradiation is included in the table. At the radiation exposures used, the combined environment of heat (158 F) and irradiation caused only slightly greater loss of tensile strength and elongation than did heat alone. Hardness increased to a slightly greater value when the material was irradiated than when subjected to heat alone, but the change in hardness was about equivalent regardless of whether exposure to radiation was at room temperature or at 158 F. Samples containing antirads were also tested. They did not appear to improve the radiation stability of the SBR wire insulation at either room temperature or the 158 F exposures. The SBR wire insulation was one of the most radiation-resistant commercial compositions tested by The B. F. Goodrich Co. (11, 51)

SBR wire-insulation compounds were tested for compression set when irradiated in air and in alkyl diphenyl ether.⁽⁵¹⁾ Samples were compressed 25 per cent and irradiated while compressed. After irradiation the compression set was determined. Table 12 lists the dose required for 50 per cent set as well as the compression set after exposure at 5.23×10^9 ergs g^{-1} (C). It may be seen from this table that compression set increases when the material is irradiated under compression, but that the compression set when irradiated is about the same, whether irradiated in air or in alkyl diphenyl ether. Goodrich workers found that SBR showed no greater resistance to radiation-induced compression set than nitrile rubber or neoprene.⁽⁵¹⁾

TABLE 12. ROOM-TEMPERATURE COMPRESSION SET OF SBR WIRE INSULATION IRRADIATED IN AIR AND IN ALKYL DIPHENYL ETHER (C₁₄-C₁₆) HYDRAULIC FLUID(51)

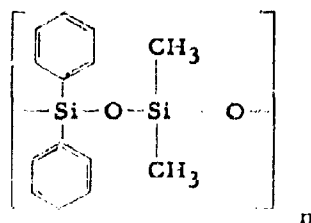
Antirad	Medium	Preirradiation Compression Set		Compression Set After Exposure at 5.73×10^9 Ergs G ⁻¹ (C), per cent	Dose Required for 50 Per Cent Compression Set, ergs g ⁻¹ (C) $\times 10^{-9}$
		Average Time, days	Average Set, per cent		
None	Air	46	33.9	83.3	0.70
Akroflex C	Air	45	33.9	80.0	1.39
Quinhydrone	Air	46	40.7	87.8	0.78
None	Hydraulic fluid	69	8.9	74.8	0.87
Akroflex C	Hydraulic fluid	69	7.5	74.1	1.64
Quinhydrone	Hydraulic fluid	66	2.3	74.3	0.91

Plastics and Resins

With plastics, physical properties generally degrade before electrical properties are seriously affected. However, their electrical resistance gradually decreases with time during irradiation, recovering after removal from the radiation field. Polystyrene and polyethylene show good insulation properties to 10^{13} and 10^{12} ergs g⁻¹ (C), respectively, while the electrical resistance of mica-glass tape impregnated with silicone resin is virtually unaffected up to 10^{14} ergs g⁻¹ (C). (52, 53)

Silicone resins, in general, are much more resistant to radiation than silicone elastomers. The major dielectric properties of solventless silicone resin are not damaged by gamma-irradiation doses as high as 1,000 megarads. These doses also have no significant effect on the physical integrity or strength of this material. Although the radiation resistance of this material is believed to be typical of those of most silicone resins, radiation has been found to destroy important dielectric properties of one silicone molding compound. These dielectric properties, however, are restored to a considerable degree by subsequent high-temperature exposure.

J. W. Ryan⁽⁵⁴⁾ reported irradiation tests using (1) General Electric resins 81132 and 11523, (2) phosphoasbestos paper, and (3) No. 3552 mica tape. The first material named is a silicone varnish having excellent heat-resistant properties. It is inert to moisture and to acid and base attack. The structure of this material is



It was chosen because of its high phenyl content.

G. E. 11523 is a silicone-bonded heavy-weave glass-fabric laminate. It is outstanding for its heat-resistant and flame-retardant properties. It can withstand temperatures to 250 C.

The phosphoasbestos paper was prepared by impregnating an asbestos mat material of an average thickness of 15 mils with a saturated solution of diammonium phosphate. It was then cured at 400 C for 6 hours. Prior to their use for this study, the materials were impregnated with a silicone oil of unknown type and composition.

The mica tape was made from selected pieces of mica, hand laid between two layers of paper. The mat was then impregnated with a silicone resin and given a partial cure.

Table 13 lists the observations of appearance and condition of the irradiated insulating materials. The phosphoasbestos paper was the most stable material tested. Because its mechanical properties are poor, initially, it is generally used with a varnish or resin. The mica tape appeared to have undergone a selective decomposition of the binder, which became brittle. The mica flakes were not discolored or affected to any appreciable degree. The decrease in abrasion resistance has been accredited to the degradation of the varnish, rather than to decomposition of the mica.

TABLE 13. OBSERVATIONS OF APPEARANCE AND CONDITION OF IRRADIATED INSULATING MATERIALS(a)

Insulating Materials	Color Change	Crazing	Cracking	Comments
<u>Exposed at Oak Ridge(b)</u>				
Silicone (G. E. 81132) cable coils	Turned dark brown	Slight	None	Embrittled
Silicone-glass (G. E. 11523) laminate	Turned dark brown	None	None	Embrittled
Silicone (G. E. 81132)-impregnated #3552	Turned dark brown	Slight	Slight	Mica unaffected
<u>Exposed at Brookhaven(c)</u>				
Silicone (G. E. 81132) cable coils	Turned green	Heavy	Slight	
Silicone-glass (G. E. 11523) laminate	Dark brown	None	None	Embrittled
Silicone (G. E. 81132)-impregnated #3552	Resin turned green	Slight	Slight	Mica relatively unaffected

(a) Ryan, J. W., "Effect of Pile Radiation on Electrical Insulation", Modern Plastics, 31 (8), 148-158 (1954).

(b) Total exposure at Oak Ridge 2.3×10^{18} nvt.

(c) Total exposure at Brookhaven 6.3×10^{18} nvt.

The results of these tests show that the dielectric properties of silicone insulation materials are not permanently affected to a significant degree by gamma radiation. Dielectric losses during irradiation are no higher than before or after the exposure. Currin concludes that, since insulation must perform both electrically and physically, the effects of radiation on physical properties limit the life. (55) At 25 C, the expected threshold dosage is between 4.5×10^9 and 1.8×10^{10} ergs g^{-1} (C) (50 and 200 megarads). At 200 C, it is between 4.5×10^8 and 3.6×10^9 ergs g^{-1} (C) (5 and 40 megarads), depending upon the insulation construction, the requirements of the application, and the silicone material used. For many nuclear applications, this life may be a number of years, depending on the radiation intensity involved.

The dielectric strength of an insulation structure composed of mica-glass tape impregnated with silicone rubber was studied at General Electric Company, Schenectady, New York. (56) Klein and Mannal reported that the presence of radiation lowered the breakdown voltage as a result of ionization. An increase in dielectric strength was observed. This is consistent with the fact that the particular silicone used undergoes additional polymerization under irradiation. It should be noted that the change in dielectric strength is only about 25 volts per 8.8×10^9 ergs g^{-1} (C) (10^8 roentgens). It is far smaller than that usually observed on irradiation of organic insulation structures.

In certain design applications, it becomes desirable to seal the insulating structure in a hermetic enclosure. Under this condition, the tendency of solid organic materials to evolve gas when subjected to nuclear radiations can be determinant in the design. Figure 10 shows the rate of gas release from a silicone-varnish-impregnated fan simile winding as a function of time as determined by Klein and Mannal. The volume of gas evolved shows no decrease in rate after a period of about 1 month. The fractional composition seems then to be approximately constant. Different grouping of molecular fractions than is observed under nuclear radiation results from high-temperature pyrolysis of the materials (Table 14). The authors conclude therefore that the processes induced by radiation are substantially different than normal deterioration of insulating materials due to temperature.

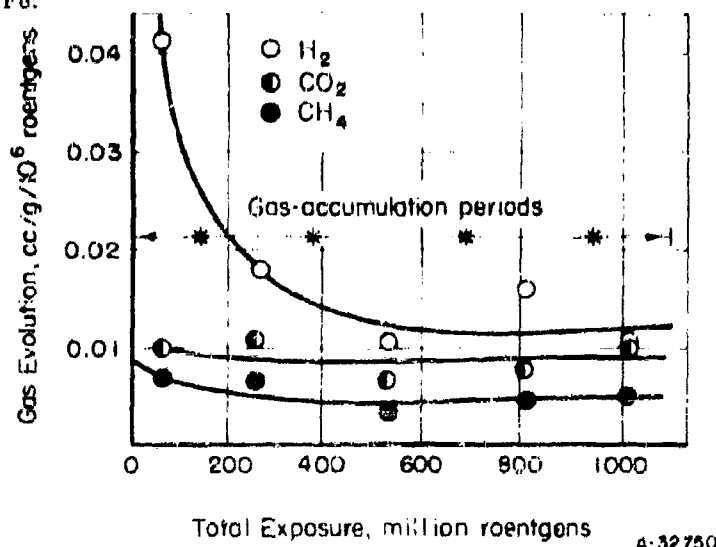


FIGURE 10. RATE OF GAS EVOLUTION FROM G. E. SR-32 SILICONE RESIN AS A FUNCTION OF TOTAL ACCUMULATED DOSE (56)

TABLE 14. GAS EVOLUTION FROM THIN FILMS OF SR-32 DURING PYROLYSIS (FILM THICKNESS 10^{-3} MM)⁽⁵⁶⁾

Time	Temp, C	Evolution Rate, microliters/min	Composition
15 min	90	0.5	Methyl trimer, tetramethylsilane and low-molecular-weight silanes
30 min	95	--	--
40 min	135	0.25	95% C_6H_6 , 4% H_2O , 1% trimer
70 hr	135	0.0042	95% C_6H_6 , 4% trimer
3 hr	150	--	C_6H_6 , H_2O , cyclic trimer, tetramers
16 hr	220	--	50% C_6H_6 , 20% hexamethyltricyclosilane

Mylar has been tested as insulation in small motors.⁽⁵⁷⁾ It became slightly brittle, but remained serviceable at 428 F when exposed to a dose of 1.4×10^9 ergs g^{-1} (C) (1.6×10^7 rep).

In insulation studies, it was found that magnetic amplifiers encapsulated in an epoxy resin changed color when irradiated to 5.1×10^9 ergs g^{-1} (C) (6×10^7 rep); however, there was no other evidence of deterioration.

Three types of epoxy potting compounds were tested at the Marquardt Corporation, Nuclear Systems Division.⁽⁵⁸⁾ These resins showed good mechanical stability to combined neutron and gamma irradiation at temperatures for which the resins were formulated. However, such compounds are probably of limited usefulness because of the effects of nuclear heating.

Miller and Liebschutz⁽⁵⁹⁾ report severe crazing of stressed polyethylene irradiated to high doses. Polyethylene-insulated thermocouple lead wires exposed to a gamma exposure dose of 2.5×10^{10} ergs g^{-1} (C) crazed considerably in the stressed areas. Vibration dislodged sections of the crazed insulation.

A polyethylene wire insulation reached a threshold at 8.7×10^9 ergs g^{-1} (C) (1×10^8 roentgens) according to another report.⁽⁶⁰⁾ This agrees quite well with the stability of polyethylene as given above.

Polypropylene has been examined for radiation stability and found to be inferior to polyethylene. At an exposure dose where polyethylene has degraded by 25 per cent, polypropylene has become useless. Even at room temperature and low relative humidity, it is too brittle after irradiation for use as electrical insulation.⁽⁶¹⁾ At an exposure dose of 8.7×10^9 ergs g^{-1} (C), it becomes brittle and loses all of its elongation and most of its tensile strength.⁽⁶²⁾

Bendix Systems Division, Ann Arbor,⁽⁶³⁾ irradiated a number of electronic components under varying neutron fluxes. Radio Set SN/ARC-34, Modulator MD-198, was operated in a nuclear environment for 335 hours at varying reactor power levels equivalent to 242 hours at a 1 megawatt level. This model was exposed to a total neutron flux

of approximately 4.35×10^{16} nvft at the face and 2.44×10^{16} at the far end, resulting in an over-all average of approximately 3.4×10^{16} nvft. The over-all average gamma dose amounted to approximately 1.45×10^9 r or 1.27×10^{11} ergs g^{-1} (C). The following conclusions can be drawn from the results of this test: (1) transformers of open frame, cast-epoxy type construction are preferred over the hermetically sealed, potted types, (2) printed-circuit boards of ceramic or glass-fiber-epoxy materials should be used in place of phenolic boards, (3) all point-to-point wiring should be done with glass-fiber or epoxy-insulated wire.

Five types of epoxy insulating and potting materials were also irradiated in the above tests. The integrated fast-neutron flux at the end of the experiment was about 1.3×10^{16} nvft. This integrated flux is based on an average fast-neutron flux of 9×10^9 nvft for the samples being irradiated. The measured fluxes at the individual sample positions varied from 7.9×10^9 to 1.0×10^{10} nvft. All types appear to be sufficiently radiation resistant to be used in potting applications up to integrated fast-neutron fluxes of 10^{16} nvft.

The effects of gamma irradiation on the thermal-aging lives and the electric strengths of a wide range of magnet wire insulations were determined by Kallander. (64) These experiments were conducted by exposing the insulation samples to the radiation field and then to the thermal and/or voltage fields. It is realized that the effects of exposure to radiation followed by exposure to temperature are not necessarily the same as the effects due to the simultaneous exposure of the insulation to the radiation and thermal fields. Consequently, the information obtained should be of value in designing and evaluating electrical equipment which may be either advertently or inadvertently (such as an atomic or nuclear blast) exposed to radiation and then placed in an operational status.

It was found that radiation affects the thermal and electrical properties of the different classes of insulation to a widely varying degree within the limits of radiation dose considered. The extent of the radiation damage ranged from very little damage to the polyester combinations even at the highest dose considered [2.63×10^{11} ergs g^{-1} (C)] (3×10^8 roentgens) all the way to total, or almost total, destruction of the tetrafluoroethylene combinations, even at the lowest dose considered [8.8×10^9 ergs g^{-1} (C)] (1×10^8 roentgens). The modified polyester, silicone enamel, glass-silicone, polyvinyl formal, polyvinyl formal-nylon combination, and epoxy combinations all give intermediate results.

Several miniaturized connectors with dielectric materials, such as phenolic, silicone resins, silicone rubber, melamine, and glass-filled diallylphthalate were irradiated at the Convair Ground Test Reactor at Ft. Worth, Texas. (65) During irradiation, the leakage resistance between adjacent pins on the connectors decreased to about one-tenth of its initial value; after irradiation, all units returned to, or exceeded, their initial leakage resistance within 15 minutes. On the basis of preliminary information, polyethylene, silicone resin, and vinyl insulation materials appear satisfactory in both electrical and mechanical properties. There was, however, evidence of some radiation damage, including HCl outgassing in polyvinyl chloride.

FilmMylar

Oriented films appear to have greater stability than the random polymer. Mylar (polyethylene terephthalate), an oriented polyester film, has been reported stable up to 10^{11} ergs g^{-1} (C), absorbed dose (10^9 rads), when subjected to electron radiation.⁽⁵⁷⁾ On the other hand, Harrington⁽²⁰⁾ indicates Mylar reaches threshold damage at an exposure dose of 4.4×10^8 ergs g^{-1} (C) (5×10^6 roentgens) and 25 per cent damage at about 8.7×10^9 ergs g^{-1} (C) (10^8 roentgens). Irradiation in vacuum to 8.7×10^9 ergs g^{-1} (C) produced the same damage as 4.4×10^9 ergs g^{-1} (C) in air, indicating that oxidation plays some part in the damage induced. Thermal aging of Mylar is unaffected up to 200 C (392 F) by irradiation, except at levels above 10^{10} ergs g^{-1} (C).

The electrical properties of Mylar are stable to an absorbed dose of 10^{10} ergs g^{-1} (10^8 rads). During irradiation, the dielectric constant and dielectric loss undergo significant changes, but they recover on removal from the radiation field.⁽⁶⁷⁾ It takes about 12 days for a 2-mil specimen to approach a quiescent state after irradiation. Dielectric constant and dielectric loss show no permanent dose-rate effect. With respect to some properties, however, Mylar does exhibit a dose-rate effect.⁽⁶⁷⁾ The effect of radiation on Mylar is generally less at higher dose rates. For example, electric strength (voltage breakdown) is considerably reduced at lower dose rates⁽⁶⁷⁾, but at higher dose rates the change is not nearly as great.

Polyethylene

Polyethylene is unaffected by radiation to an absorbed dose of 1.9×10^9 ergs g^{-1} (C) and accrues 25 per cent damage at 9.4×10^9 ergs g^{-1} (C).⁽⁵⁾ Harrington and Giberson⁽²⁰⁾ observed a somewhat lower threshold value for polyethylene when irradiating 3, 5, 10, and 15-mil films. There were no major differences in the radiation resistance of these films. All showed a considerable change in properties between 4.4×10^8 ergs g^{-1} (C) (5×10^6 roentgens) and 8.7×10^8 ergs g^{-1} (C) (10^7 roentgens). The 15-mil films showed a greater increase in tensile strength at lower doses than the thinner films.

Polyethylene is subjected to oxidation when irradiated. This is one reason that thin films are degraded at lower radiation dosages than thicker films. However, polyethylene shows very little postirradiation oxidation.⁽⁶⁸⁾ Samples irradiated by cobalt-60 to an exposure dose of 6.2×10^8 ergs g^{-1} (C) did not undergo oxidation after irradiation.

High-density polyethylene is much more crystalline than the low-density types, and its radiation resistance may be expected to be different. A 2-mil film of Marlex was extremely brittle and crumbly after 4.4×10^9 ergs g^{-1} (C) (5×10^7 roentgens). Even at 4.4×10^8 ergs g^{-1} (C) (5×10^6 roentgens) elongation had decreased by 92 per cent and tensile strength had decreased by 12 per cent. However, according to Harrington and Giberson⁽²⁰⁾, in thicker films Marlex behaves more like the lower density polyethylene. Table 15 shows the change in elongation and tensile strength with increasing radiation exposure for low- and high-density polyethylene.

TABLE 15. MECHANICAL PROPERTIES OF IRRADIATED POLYETHYLENE(20)

Material and Thickness	Exposure Dose		Initial Properties and Per Cent Change			
	ergs g ⁻¹ (C)	roentgen x 10 ⁻⁶	Elongation		Tensile Strength	
			Per Cent	Δ%	Psi	Δ%
Alathon 3, NC-10 (0.003 in.)	0	0	380		1915	
	4.4 x 10 ⁸	5		-3.7		1.1
	8.7 x 10 ⁸	10		-7.9		-2.5
	4.4 x 10 ⁹	50		-86.8		-33.7
	8.7 x 10 ¹⁰	100		-95.8		-32.8
	8.7 x 10 ¹⁰	100-V(a)		-50.0		46.4
Alathon 3, NC-10 (0.005 in.)	0	0	510		2330	
	4.4 x 10 ⁸	5		5.1		9.8
	8.7 x 10 ⁸	10		-3.0		-4.2
	4.4 x 10 ⁹	50		-84.1		-42.5
	8.7 x 10 ¹⁰	100		-84.9		-42.7
	8.7 x 10 ¹⁰	100-V		-67.5		8.2
Alathon 3, NC-10 (0.010 in.)	0	0	570		2825	
	4.4 x 10 ⁸	5		3.0		6.5
	8.7 x 10 ⁸	10		-3.3		-8.2
	4.4 x 10 ⁹	50		-81.8		-57.2
	8.7 x 10 ¹⁰	100		-91.6		-57.7
	8.7 x 10 ¹⁰	100 V		-65.9		1.6
Alathon 3, NC-10 (0.015 in.)	0	0	650		2330	
	4.4 x 10 ⁸	5		-10.6		17.8
	8.7 x 10 ⁸	10		-10.9		22.2
	4.4 x 10 ⁹	50		-82.7		-42.7
	8.7 x 10 ¹⁰	100		-90.4		-40.2
	8.7 x 10 ¹⁰	100-V		-73.1		7.1
Marlex 50 (0.002 in.)	0	0	600		4280	
	4.4 x 10 ⁸	5		-91.7		-12.7
	8.7 x 10 ⁸	10		-97.8		-35.3
	4.4 x 10 ⁹	50		-100.0		-100.0
	8.7 x 10 ¹⁰	100		--		--
	8.7 x 10 ¹⁰	100-V		-95.3		-7.5

(a) Irradiated in a vacuum.

Polycarbonate

Harrington and Giberson⁽²⁹⁾ irradiated polycarbonate films (Lexan and Macrofol). Figure 11 shows the chemical and physical changes induced by exposure to gamma radiation in air at 25 C. At the initial exposure dose of 4.3×10^8 ergs g^{-1} (C), these materials exhibited a slight improvement in both tensile strength and elongation. Both properties decreased gradually to 4.3×10^9 ergs g^{-1} (C). Further exposure to 8.7×10^9 ergs g^{-1} (C) increased the rate of degradation, but the materials were in good condition and possessed much of their original flexibility and toughness. When exposed to 2.6×10^{10} ergs g^{-1} (C), Lexan became quite brittle and could not be tested for physical properties.

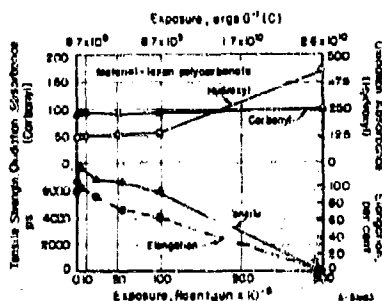


FIGURE 11. CHEMICAL AND PHYSICAL CHANGES IN A POLYCARBONATE PLASTIC, WHICH WERE INDUCED BY EXPOSURES TO GAMMA RADIATION IN AIR AT 25 C

The properties of Macrofol were changed about equally for both air and vacuum irradiation to 8.7×10^9 ergs g^{-1} (C) (1×10^8 roentgens). This would indicate that oxidation does not play a major role in the degradation of carbonate plastics. It is suggested that chain cleavage or depolymerization may be responsible for the radiation damage.

Polyvinyl Chloride

The radiation stability of polyvinyl chloride appears to be directly related to sample thickness. An 80-mil thick Geon 2046 compound was found to be stable to nuclear radiation to an absorbed dose of 1.9×10^9 ergs g^{-1} (C) and changed by 25 per cent at 1.1×10^{10} ergs g^{-1} (C).⁽⁶⁹⁾ Harrington and Giberson⁽⁶⁷⁾ reported two additional Geon compounds, 8630 and 8640, had somewhat lower radiation stability. These compounds were 4 and 20 mils thick, respectively, and showed a radiation-sensitive threshold at an exposure dose less than 4.4×10^8 ergs g^{-1} (C) (5×10^6 roentgens) and 25 per cent damage at approximately 4.4×10^9 ergs g^{-1} (C) (5×10^7 roentgens). Table 16 lists the changes in elongation and tensile strength found by Harrington and Giberson. These data show that the thicker samples are the more stable, especially at the lower exposures levels.

TABLE 16. CHANGE IN PHYSICAL PROPERTIES OF POLYVINYL CHLORIDE DUE TO IRRADIATION⁽⁸⁾

	Exposure Dose		Elongation		Tensile Strength	
	ergs g ⁻¹ (C)	roentgens x 10 ⁻⁶	Per Cent	%	Psi	%
Geon 8630 (0.004 in.)	0	0	245		2585	
	4.4 x 10 ⁸	5		-10.7		-25.6
	8.7 x 10 ⁸	10		-21.3		-34.5
	4.4 x 10 ⁹	50		-26.5		-36.2
	8.7 x 10 ⁹	100		-38.8		-31.5
Geon 8630 (0.020 in.)	0	0	300		2735	
	4.4 x 10 ⁸	5		4.0		-5.7
	8.7 x 10 ⁸	10		4.6		-6.2
	4.4 x 10 ⁹	50		-19.2		-10.2
	8.7 x 10 ⁹	100		-28.3		-6.0
Geon 8640 (0.004 in.)	0	0	225		3150	
	4.4 x 10 ⁸	5		-8.5		-13.3
	8.7 x 10 ⁸	10		-11.8		-28.1
	4.4 x 10 ⁹	50		-44.4		-44.4
	8.7 x 10 ⁹	100		-46.7		-42.3
	8.7 x 10 ⁹	100-V(a)		-29.1		-22.4
Geon 8640 (0.020 in.)	0	0	325		3580	
	4.4 x 10 ⁸	5		-5.3		-5.1
	8.7 x 10 ⁸	10		-2.2		-4.1
	4.4 x 10 ⁹	50		-22.2		-32.0
	8.7 x 10 ⁹	100		-32.3		-31.2

(a) Irradiated in vacuum.

Hoses

Standard aircraft and missile hoses and couplings contain organic polymeric materials which are affected significantly by nuclear radiation. To determine the functional life of these items when exposed to radiation, some tests have been conducted at controlled conditions of temperature, pressure, type of internal fluid, and radiation-exposure rate. Buna N, a solvent-resistant synthetic rubber, and Teflon, a temperature-resistant plastic, were the hose materials used in most of these tests.

Table 17 summarizes gamma-radiation tests conducted by General Electric-ANP Division, Cincinnati, Ohio, under conditions simulating actual operation for a specified time or until leakage occurred. Of these two types of hose materials, Buna N was affected less by the radiation and appeared to be functionally satisfactory at exposure doses up to about 4×10^8 ergs g⁻¹ (C), at temperatures up to 350 F and static pressures of 1,200 psig. An intermittent-pressure test (0 to 1,000 psig) at 350 F indicated Buna N to be satisfactory to at least 1×10^8 ergs g⁻¹ (C).

The Teflon-hose tests at similar conditions showed that this material failed at lower exposure doses - about 1×10^8 ergs g⁻¹ (C) for static pressure and 1×10^7 ergs g⁻¹ (C) for intermittent pressure. The exposure dosage-failure relationship was practically independent of temperature from 100 to 350 F. An empirical correlation of dosage, time to failure, and temperature was derived.⁽⁸⁾

TABLE 17. SUMMARY OF RADIATION TESTS ON HOSES AND COUPLINGS BY GENERAL ELECTRIC - ANP DIVISION

Material or Part Number	Temperature, F	Test Conditions (a)			Duration of Test, hours	Exposure Dose, $\text{ergs g}^{-1} (\text{C})$	Effect of Test on Hose				Reference
		Fluid in Hose	Fluid Pressure, PSIG	Fluid Pressure, $\frac{\text{lb}}{\text{sq in}}$			Stiffness	Oil Diffusion	Rupture	Effect of Flexing	
Standard J-47 jet-engine fuel-hose assemblies (AN-8264-4-10-3/4)			650 to 700	Static							
	250			Static	408	3.9×10^8	Slight	None	None	None	(102)
	350	JP-4	1200	Static	378	7.1×10^8	Very stiff	None	None	Leak; crumbled	
	350	JP-4	1200	Static	119	1.5×10^9	Very stiff	Slight	None	Burst; crumbled	
	400	JP-4	1200	Static	56	3.0×10^9	Very stiff	Great	Leak	Burst; crumbled	
Buna N											
	250		1200	Static	408	4.5×10^8			None		(66)
	350	JP-4	1200	Static	378	4.0×10^8			None	(b)	
	350	JP-4	1200	Static	119	1.3×10^8			Leak	(b)	
	400	JP-4	1200	Static	56	0.6×10^8			Leak	(c)	
Buna N	350	MIL-L-7808C	0 to 1200	Intermittent (15-minute intervals)	180	1.1×10^8			None		(66)
Teflon											
	100	MIL-L-7808C	1200	Static	140	1.5×10^8			Leak		(8, 66)
	200	MIL-L-7808C	1200	Static	70	9.8×10^8			Leak		
	250	MIL-L-7808C	1200	Static	35	1.0×10^8			Leak		
	250	MIL-L-7808C	1200	Static	139	1.2×10^8			Leak		
Teflon	350	MIL-L-7808C	1200	Static	58	0.9×10^8			Leak	(d)	
	300	MIL-L-7808C	0 to 1200	Intermittent (15-minute intervals)	27.5	3×10^7			Leak		(8, 66)
	350	MIL-L-7808C	1000		3.75	1×10^7			Leak		

(a) The gamma flux was $1.1 \times 10^6 \text{ ergs g}^{-1} (\text{C}) \text{ hr}^{-1}$.

(b) Unirradiated hose of the same material failed after 182 hours at otherwise similar test conditions.

(c) Unirradiated hose of the same material failed after 315 hours at otherwise similar test conditions.

(d) No failure of unirradiated hose after 1150 hours at otherwise similar test conditions.

Nitrile-rubber hoses⁽¹⁶⁾ were used by Barnett and Baxter at General Electric in simulated turbojet accessory systems. They were satisfactory at temperatures from 190 to 300 F at a gamma dose of 1.75×10^8 ergs g^{-1} (C). The fluids used were MIL F-7024 fuel, MIL-7808C lubricant, and a high-temperature hydraulic fluid, OS-45. Fluid pressure was varied from 75 to 1,000 psig at 10 cycles per hour.

Workers at The B. F. Goodrich Co. ^(11,51) conducted tests on the combined effects of radiation and elevated temperatures on rubber compounds. In these tests a hose tube stock, based on Neoprene GN, was irradiated and tested at room temperature and 158 F. The results of these tests are shown in Table A-40. This stock was also irradiated while compressed 25 per cent, and the compression set determined. Table 18 gives the compression set after irradiation both in air and while immersed in an alkyl diphenyl ether (C₁₄-C₁₆) hydraulic fluid. Neoprene is reported to swell badly in the alkyl diphenyl ether hydraulic fluid.

TABLE 18. COMPRESSION SET OF NEOPRENE AIRCRAFT COMPOUNDS IRRADIATED IN AIR AND IN ALKYL DIPHENYL ETHER (C₁₄-C₁₆) HYDRAULIC FLUID⁽⁵¹⁾

Compound	Antirad	Environment	Preirradiation Compression Set		Compression Set After Exposure at $5, 23 \times 10^9$ Ergs G^{-1} (C)	Dose Required for 50 Per Cent Compression Set, 10^9 Ergs G^{-1} (C)
			Average Time, days	Average Set, per cent		
Wire insulation	None	Air	40	49.3	81.7	1.95
	Akroflex C	Air	45	45.0	78.5	1.31
	Quinhydrone	Air	40	49.4	79.2	1.57
	None	Hydraulic fluid	70	37.4	80.3	1.07
	Akroflex C	Hydraulic fluid	64	40.1	83.8	1.58
	Quinhydrone	Hydraulic fluid	67	37.0	70.7 ^(a)	
	None	Air	40	20.4	75.3	1.31
	Akroflex C	Air	47	16.2	75.8	2.18
	Quinhydrone	Air	40	42.0	82.3	0.70
Packing compound	None	Hydraulic fluid	73	8.7	84.3	1.22
	Akroflex C	Hydraulic fluid	71	7.1	70.7	1.80
	Quinhydrone	Hydraulic fluid	72	23.0	79.3	1.20
	None	Air	48	36.5	74.1	1.48
	Akroflex C	Air	48	42.7	70.1	1.06
	Quinhydrone	Air	48	32.7	79.1	1.60
	None	Hydraulic fluid	70	25.1	77.3	1.06
	Akroflex C	Hydraulic fluid	67	30.7	75.2	1.32
	Quinhydrone	Hydraulic fluid	69	20.4	79.3	1.07

(a) Compression set after exposure at 4.36×10^9 ergs g^{-1} (C).

Laminates

The reinforced plastic materials currently used for structural applications in aircraft consist primarily of glass fabrics laminated with a thermosetting resin. The

principal organic binders generally used for these laminates are silicones, phenolics, polyesters, heat-resistant polyesters, epoxy, and heat-resistant epoxy resins.

Several silicone, phenolic, polyester, epoxy, and polyurethane resins were examined by Tomashot⁽⁷⁰⁾ as components of glass fabric laminates to be used as plastic radome materials in a nuclear environment. The mechanical properties of the materials were not significantly affected, except for Epon 1001 (an epoxy resin) at doses through 8.7×10^{10} ergs g^{-1} (C). The failure of Epon 1001 was thought to be due to the catalyst used. The style of weave used in the glass fabric did not noticeably affect the durability of the finished laminate to environmental conditions. None of the materials showed any significant change in electrical properties due to radiation.

These materials were irradiated in a gamma flux, not in a mixed flux of gammas and neutrons. It has not been determined whether neutron doses would adversely affect the glass fabrics. Also, the heat-resistant materials were heated after irradiation; simultaneously heating and irradiating the materials may give different results. The results of these tests are shown in Table A-41.

Higberger⁽⁷¹⁾ irradiated two other radome materials, a TAC-polyester laminate and a silicone laminate in a mixed-flux environment [1.7×10^9 ergs g^{-1} (C)] at ambient temperature. Mechanical tests were performed in a dry atmosphere at room temperature, at 450 F and after a 1/2-hour exposure, and at 500 F after a 100-hour exposure. The polyester laminate displayed less deterioration in strength and modulus when tested at elevated temperatures, whereas the silicone laminate was better at room temperature. The results of these tests are summarized in Table A-42. Mixer, at Stanford Research Institute⁽⁷²⁾, studied the effects of radiation on structural laminates made from eight resin-catalyst systems. These were irradiated to 10^{11} ergs g^{-1} (C) to determine the threshold for damage. Laminates irradiated included:

Resin-Catalyst System	Resin Type
Epon 828 + Curing Agent A	Epoxy
Epon 1001 + diacydianamide	"
Epon X-131 + BF ₃ 400	"
Epon X-131 + diacydianamide	"
Laminac 4232 + benzoyl peroxide	Polyester
Selectron 5003 + benzoyl peroxide	"
CTL 91-LD Phenolic	Phenolic
DC-2106 + XY-16	Silicone

According to Mixer, all of the laminates failed by about 50 per cent at 10^{12} ergs g^{-1} (C), except the phenolic CTL 91-LD which maintained all physical properties, with the possible exception of compressive strength, at 500 F. (See Table A-41.) In comparing the work of Mixer with that of Tomashot, it will be noted that there is a decided drop in strengths of these laminates between the radiation doses of 8.7×10^{10} ergs g^{-1} (C) and 8.5×10^{11} ergs g^{-1} (C). The only exception is the aforementioned phenolic material CTL 91-LD.

The effects of radiation on 12 kinds of laminates were studied by Bauerlein⁽⁷³⁾ at Convair, Fort Worth, Texas. Of the twelve kinds of laminates, six were impregnated with phenolic resin, four with epoxy resin, and two with polyester resin. Irradiation was carried out at four dose levels and at an uncontrolled ambient temperature

estimated to be between 70 and 80 F for the three lower doses and approximately 160 F for the highest dose. Average test results for each set of test specimens are tabulated in Table A-43. Bauerlein also examined the effects of radiation on Hexcel 91LD and Hexcel F-120 honeycomb core reinforced with glass fiber. (74) Both materials had a phenolic-resin base. The same temperatures and doses used in the preceding work were used in this experiment.

A review of the four dose-level groups reveals that no effects due to the varying dose can be detected. The average compressive strength of the control specimens and the average specimen strength of each of the four dose-level groups for both types of honeycomb core are shown in Table A-44. The difference between the maximum and minimum strength of the specimens within each group ranged from 130 to 250 psi. Bauerlein concluded that the compressive strength of neither Hexcel 91LD nor Hexcel F-120 honeycomb core reinforced with glass fiber was affected by the various dose levels. The honeycomb cores are suitable from a compression standpoint for use in a nuclear environment that does not exceed the equivalent of 9.3×10^9 ergs g^{-1} (C) gamma dose. Plans are under way to study the suitability of these materials under environmental irradiation conditions. Other physical properties, such as tensile strength and modulus of rigidity, are being studied.

Studies of laminated plastic radome materials have shown them to be essentially unchanged by radiation with respect to dielectric constant and loss tangent. (4) Their selection is, therefore, mainly determined by structural stability under conditions of heat, stress, and radiation.

Silicone Laminates

Glass laminates fabricated with silicone resins show exceptionally good radiation resistance. They reach a threshold of degradation when exposed to gamma-radiation doses to 10^{11} ergs g^{-1} (C). (75) Phenolic-silicone laminates show even better resistance to radiation. Bopp and Sieman (76) report that the hardening of silicone-glass laminates indicates that crosslinking is the predominant radiation-produced process.

Keller (9) determined the threshold of degradation caused by gamma radiation for silicone-glass fiber reinforced laminates and studied the combined effects of heat and radiation on these laminates. At room temperature, silicone laminates reach threshold damage at about 10^{11} ergs g^{-1} (C). However, tensile strength does not drop off until 2.49×10^{11} ergs g^{-1} (C). The combination of heat and radiation was no more detrimental than heat alone to the flexural strength of these laminates, except at the highest exposure dose [8.3×10^{11} ergs g^{-1} (C)]. (See Table 19.) The wet flexural strength of silicone laminates irradiated at 8.3×10^{10} ergs g^{-1} (C) is approximately 50 per cent of control strength. The compressive-test results after 1/2 hour at 500 F in air show degradation at 8.3×10^{11} ergs g^{-1} (C) and at 2.49×10^{11} ergs g^{-1} (C) after a 2-hour boil. The tensile-test results after a 2-hour boil show degradation at 8.3×10^{11} ergs g^{-1} (C). The results of these tests are summarized in Tables 20 and 21.

Flexural-strength loss in silicone-glass cloth laminates irradiated at 500 F has been found to be due to the effect of heat rather than to irradiation. (9) The flexural strength of laminates exposed to 4.15×10^9 ergs g^{-1} (C) at 500 F (100 hrs) was only about 15 per cent less than that of laminates exposed to 500 F with no irradiation. However, flexural strength of the laminates exposed to heat alone for the same period of time decreased to approximately 42 per cent of the original value.

TABLE 19. MECHANICAL PROPERTIES OF GLASS FABRIC-REINFORCED PLASTIC LAMINATES AFTER IRRADIATION(2)

Exposure	Material	Room-Temp Tensile, Dry, psi	Tensile, 2-Hour Boil, psi	Room-Temp Comp., Dry, psi	Comp., 2-Hour Boil, psi	Comp., 1/2 Hour 500 F, psi	Room-Temp Flexural, Dry, psi	Flexure, 2-Hour Boil, psi	Flexure, 1/2 Hour 500 F, psi	Flexural Modulus, 10^6 psi Room Temp	2-Hour Boil	1/2 Hour 500 F
1	Polyester	43,650		37,400			65,870			3.21		
2		43,070		25,370			64,070			3.08		
3		44,500	35,000	24,500	15,000		61,300	36,800		3.36	2.88	
4		43,920	34,730	12,370	9,270		16,350	10,600		2.53	2.24	
1	Heat-resistant polyester		34,630		26,000	18,350		51,250	20,130		2.60	2.16
2			34,290		18,300	9,540		51,570	13,660		2.54	1.68
3			32,700		18,400	2,600		41,900	9,220		2.71	1.44
4			26,660		10,180	2,890		24,500	9,330		2.29	1.42
1	Phenolic		29,530		35,000	40,730		55,300	46,010		2.21	2.72
2			28,550		41,300	35,800		68,850	47,370		2.47	2.95
3			26,830		55,000	37,200		62,000	46,500		3.60	3.17
4			25,730		51,920	15,450		62,850	48,960		3.32	2.36
1	Silicone		27,350		4,460	5,440		23,150	12,940		2.05	1.58
2			34,250		6,900	6,600		10,800	13,640		1.93	1.88
3			33,000		1,250	7,400		8,110	13,600		--	--
4			16,240		--	1,180		1,650	5,980		0.64	1.75
1	Heat-resistant epoxy		48,300		42,900	13,810		73,300	31,370		3.19	3.08
2			51,250		42,350	8,140		82,450	16,250		3.44	2.15
3			52,200		17,800	5,450		46,100	12,900		--	--
4			45,370		3,550	2,660		17,450	9,010		2.42	1.31
1	Epoxy		53,750		47,730			86,800			3.79	3.39
2			58,600		54,550			90,900			3.83	3.19
3			56,200		58,500	39,050		71,500			4.15	3.82
4			44,410		13,510	9,250		30,300			--	3.333

Note: Exposure 1 = control.

Exposure 2 = 8.3×10^{10} ergs cm^{-2} (C).Exposure 3 = 2.49×10^{11} ergs cm^{-2} (C).Exposure 4 = 8.3×10^{11} ergs cm^{-2} (C).

TABLE 20. MECHANICAL PROPERTIES OF GLASS-FABRIC-REINFORCED SILICONE LAMINATES AFTER IRRADIATION (9)

Exposure	Material	Tensile, 2-Hour Boil, psi	Compressive, 2-Hour Boil, psi	Compressive, 1/2 Hour at 500 F, psi	Flexure, 2-Hour Boil, psi	Flexure, 1/2 Hour at 500 F, psi	Flexural Modulus, 10^6 psi	
							2-Hour Boil	1/2 Hour at 500 F
Control	Silicone	27,350	4,480	6,400	23,150	12,940	2.05	1.58
8.3×10^{10}		34,250	6,900	6,000	10,800	13,640	1.93	1.88
2.49×10^{11}		33,000	3,230	7,400	8,110	13,605	--	--
8.3×10^{11}		19,240	--	1,180	1,650	5,980	2.42	1.31

TABLE 21. MECHANICAL PROPERTIES OF GLASS-FABRIC-REINFORCED SILICONE LAMINATES AFTER IRRADIATION AT ELEVATED TEMPERATURES (9)

Material	Test	Radiation, 10^9 ergs g^{-1} (C)	Temperature, F	Exposure Time, hours	Ultimate Strength, psi	Flexural Modulus, 10^9 psi
Silicone	Flexure	None	Room	None	31,760	3.06
		8.3	Room	200	31,460	2.94
		None	500	50	12,390	1.90
		2.1	500	50	13,625	2.0
		None	500	100	13,410	2.0
		4.15	500	100	11,720	2.0
		None	500	200	14,660	2.0
		8.3	500	200	9,860	1.9

Asbestos-silicone laminates have been tested at room temperature and have shown no apparent change in properties⁽⁷⁷⁾ to an absorbed dose of 1.1 to 2.0×10^{10} ergs g^{-1} (C) (1.1 to 2.0×10^8 rads). At 6×10^{10} ergs g^{-1} (C) (6×10^8 rads), tensile strength increased 10 per cent, shear strength decreased 5 per cent, hardness increased 5 per cent, while the gas evolved amounted to 7 ml/g.

A silicone-glass cloth laminate exposed to a gamma flux of 1.3×10^{11} photons $cm^{-2} sec^{-1}$ for a period of 3 months suffered neither color nor dimensional changes. Assuming an average photon energy of 1 Mev, this is a dose of about 5×10^{10} ergs g^{-1} (C). However, its insulation resistance jumped from 10^2 to 9×10^3 megohms.⁽⁷⁶⁾ Thus, it appears that fillers such as glass cloth improve radiation resistance.

Warrick, Fischer, and Zack⁽⁷⁸⁾ studied the effect of radiation on two silicone resin-glass laminates, DC-2106 and DC-2105. The results of these tests are presented in Table 22. At room temperature the flexural strength decreased approximately 12 per cent for DC-2106 and 35 per cent for DC-2105 at 8.3×10^{10} ergs g^{-1} (C) (10^9 rads). At 250 C, and the same radiation dose, the flexural strength of the nonirradiated samples had dropped 64 per cent for DC-2106 and 90 per cent for the DC-2105 resin. After irradiation, the drop in these values at 250 C was 57 and 75 per cent, respectively. Thus, it appears that the degradative effect of heat alone is greater than that resulting from a combination of heat and radiation.

TABLE 22. EFFECTS OF RADIATION ON SILICONE-GLASS LAMINATES⁽⁷⁸⁾

Resin	Flexural Strength, psi	
	Original	After 8.3×10^{10} Ergs G^{-1} (C) (10^9 Rads)
	<u>Tested 25 C</u>	
2106	41,406	36,300
2105	40,700	26,500
	<u>Tested 250 C</u>	
2106	14,700	17,600
2105	4,180	9,970

Samples of MS 2103 and MS 2104 laminates made with Y-227 glass cloth, supplied by Fothergill and Harvey, Limited, Littleborough, Lancashire, England, were press cured for 30 minutes at 175 C.⁽⁷⁹⁾ Flexural strengths were measured at 250 C after exposures to 2.7×10^9 ergs g^{-1} (C) (31.5 Mrep) of gamma rays. Since no improvement, such as would be obtained with an oven cure, was noted, it is apparent that the radiation dose had little or no effect, even though such an amount of radiation has a large effect on dimethyl silicone rubbers.

At an integrated dose of 2.5×10^9 ergs g^{-1} (C) [6×10^{14} n cm^{-2} for fast neutrons, 6×10^{13} (nv₀)t for thermal neutrons, and 5×10^{16} photons cm^{-2} for gamma rays], Johnson and Sicilio at Convair found that tensile strength and tear resistance decreased for Orlon laminated with DC-X-6015A silicone.⁽⁸⁰⁾ (See Table A-45.) No significant change in these same properties was noted when Dacron was laminated with DC-X-6015A silicone. Glass cloth laminated with silicone (postformable sheet) showed a decrease in water absorption and dielectric strength and an increase in arc resistance. No significant differences were noted in other properties at this dose.

Phenolic Laminates

As mentioned previously, phenolic, polyester, epoxy, and silicone laminates had been irradiated to 8.7×10^{10} ergs g^{-1} (C) by Tomashot⁽⁷⁰⁾ at WADC. Keller⁽⁹⁾ extended this study to include doses to 8.3×10^{11} ergs g^{-1} (C) at both room temperature and short times at 500 F and to 8.3×10^9 ergs g^{-1} (C) for long times at 500 F. The results of these tests are presented in Tables 19 and 23, respectively.

TABLE 23. MECHANICAL PROPERTIES OF GLASS-FABRIC-REINFORCED PLASTIC LAMINATES AFTER IRRADIATION AT ELEVATED TEMPERATURE⁽⁹⁾

Material	Test	Exposure Dose, 10^9 ergs g^{-1} (C)	Temperature, F	Exposure Time, hours	Ultimate Strength, psi	Flexural Modulus, 10^6 psi
Silicone	Flexure	None	Room	None	31,760	3.08
		8.7	Room	200	31,490	2.94
		None	500	50	12,990	1.90
		2.1	500	50	13,625	2.0
		None	500	100	13,410	2.0
		4.15	500	100	11,720	2.0
		None	500	200	14,080	2.0
		8.3	500	200	9,880	1.9
Heat-resistant epoxy	Compression	None	Room	None	46,680	
		8.3	Room	200	46,680	
		None	500	50	3,705	
		2.1	500	50	3,780	
		None	500	100	4,090	
		4.15	500	100	5,490	
		None	500	200	4,720	
		8.3	500	200	4,360	
Phenolic	Flexure	None	Room	None	84,525	4.22
		8.3	Room	200	84,040	4.35
		None	500	50	27,300	3.14
		2.1	500	50	53,020	3.40
		None	500	100	17,600	2.62
		4.15	500	100	47,015	3.61
		None	500	200	12,330	2.13
		8.3	500	200	15,645	2.41

The phenolic laminate maintained all its physical properties after 1/2 hour at 500 F after a radiation dose of 8.5×10^{11} ergs g^{-1} (C), with the possible exception of compressive strength (Table 19). At 550 F (Table 23) and up to an exposure dose of 4.15×10^9 ergs g^{-1} (C), the flexural strengths of the irradiated phenolic laminates were approximately twice those of the phenolic laminates subjected to heat alone. At 8.3×10^9 ergs g^{-1} (C), the values were slightly higher for the laminates irradiated at 500 F.

Phenolic laminates were also irradiated to exposure doses of 2.1×10^9 ergs g^{-1} (C) (50 hours) at temperatures of 500, 600, 700, 800, and 900 F.⁽⁸¹⁾ Control specimens were tested after 1/2 hour at the test temperature with no irradiation. At 500, 600, and 900 F, flexural strengths of the irradiated laminates were higher than those of the controls. At 700 and 800 F, they were also higher. Thus, combined heat and irradiation causes no more, or perhaps less, degradation to phenolic laminates than does high

temperature alone. Keller points out that a phenolic system ordinarily deteriorates when exposed to elevated temperatures in the presence of air due to oxidation. He suggests that it is possible that irradiation inhibits the oxidation and that crosslinking takes place.

Polyester Laminates

Polyester laminates also show good radiation stability. Johnson and Sicilio⁽⁸⁰⁾ irradiated several types of glass fiber-polyester laminates used in aircraft construction to a total dose of approximately 2.4×10^9 ergs g^{-1} (C) [6×10^{14} fast n cm^{-2} , 6×10^{13} (nv) γ t, and 5×10^{16} gamma photons cm^{-2}]. No major changes in the physical properties of the laminates were found after this exposure.

Keller⁽⁹⁾, in an effort to determine threshold damage for laminates, irradiated a regular polyester and a heat-resistant (TAC) polyester to 8.3×10^{11} ergs g^{-1} (C). When irradiated at room temperature, the TAC-polyester reaching threshold damage between 8.3×10^{10} and 2.49×10^{11} ergs g^{-1} (C) was less resistant to radiation than the regularly cured polyester which reached threshold damage between 2.49×10^{11} and 8.3×10^{11} ergs g^{-1} (C) (see Table 19). These laminates were not irradiated at elevated temperatures.

Epoxy Laminates

Keller⁽⁹⁾ tested a heat-resistant epoxy and a regular epoxy laminate to determine the dosage for threshold damage at room temperature. Both laminates contained glass fiber as the reinforcing agent. The regular epoxy laminate reached a radiation threshold damage somewhat beyond 2.5×10^{11} ergs g^{-1} (C), but a significant loss of strength did not occur until 8.3×10^{11} ergs g^{-1} (C). The heat-resistant epoxy resin showed some degradation after an exposure dose of 8.3×10^{11} ergs g^{-1} (C). (See Table 19.)

In addition to room-temperature studies, the heat-resistant epoxy laminate was irradiated at 500 F for 200 hours to a total exposure dose of 8.3×10^9 ergs g^{-1} (C). Compressive strength dropped considerably when laminates were subjected to heat alone. However, the effect of heat and radiation together was not as severe as that of heat alone (see Table 23).

Polyurethane Laminates

Bonanni⁽⁸²⁾ reported on the physical properties of a new urethane laminate. In this work the effects of radiation (cobalt-60) on flexural strength and modulus and weight loss were determined. Very little change in either flexural strength or modulus was noted up to a dose of approximately 7×10^{10} ergs g^{-1} (C), the highest dose reported. Weight remained constant to about 1.75×10^{10} ergs g^{-1} (C) and then began to drop, with 1 per cent loss being noted after 7×10^{10} ergs g^{-1} (C).

Tomashot⁽⁷⁰⁾ determined the ultimate flexural and flatwise compressive strengths of polyurethane foam sandwich construction after irradiation. The foam sandwich samples showed no reduction in mechanical properties up to 10^{11} ergs g^{-1} (C), the largest dose to which the samples were subjected.

O-Rings and Backup Rings

O-Rings

O-rings made from a number of rubber types have been evaluated under radiation. For high-temperature applications, Viton A (copolymer of hexafluoropropylene and vinylidene fluoride) appears to be the best available material for O-rings, although its radiation resistance is not as great as desired. However, in many applications it is serviceable.

Trepus at Boeing⁽¹³⁾ tested Viton A O-rings in MLO-8200 or Versilube F-50 hydraulic fluid during irradiation at 400 F. Radiation exposure doses were 8.39×10^8 , 8.39×10^9 , and 8.39×10^{10} ergs g⁻¹ (C). These rings were installed with spiral Teflon backup rings. Samples irradiated at 8.39×10^8 ergs g⁻¹ (C) retained most of their elastomeric properties and sealing ability. Those irradiated to 8.39×10^9 ergs g⁻¹ (C) became considerably harder but still retained their sealing ability. Exposure to 8.39×10^{10} ergs g⁻¹ (C) caused the O-rings to become very hard and brittle and to lose their sealing ability. Those irradiated in MLO-8200 sealed better under all test conditions (static pneumatic and hydraulic pressure and pulsed hydraulic pressure) than did those irradiated in Versilube F-50.

Miller at Lockheed⁽¹⁴⁾ tested an electrohydraulic flight control for 380 hours at a temperature of 200 F and pressures up to 3,000 psi. The exposure dose was 5×10^9 ergs g⁻¹ (C). Oronite 8200 hydraulic fluid and Viton A and nitrile rubber O-rings were used in the system. The Viton A O-rings sealed perfectly in the static seals although they underwent pronounced compression set. With dynamic seals, Viton A permitted some leakage during the final stages of the test. The physical properties of the nitrile rubber O-rings changed less than those of Viton A.

In a subsequent test, MacCullen at Lockheed⁽¹⁵⁾ tested an electrohydraulic servo test loop containing Viton A and Buna N (nitrile rubber) O-rings. Oronite 8518, a modification of the 8200, was the hydraulic fluid used in the system. The test was conducted for 260 hours with an average radiation dose rate of 1.1×10^7 ergs g⁻¹ (C) hr⁻¹. Fluid temperature was maintained at 275 F, and the pressure was 3,000 psi. In this test, the Viton A seals leaked and did not perform satisfactorily. This was attributed, in part, to the fact that the seals were slightly undersize due to shrinkage when molded, and in part to the synergistic effects of temperature and radiation. The Viton A rings, exposed to 1.4 to 4.9×10^9 ergs g⁻¹ (C), were very brittle when removed, although they recovered considerable elasticity after removal.

Barnett and Baxter at General Electric⁽¹⁶⁾ ran four 200-hour thermal-radiation tests on simulated turbojet accessory systems. Three fluids, MIL-F-7024 fuel, MIL-L-7808C lubricant, and a high-temperature hydraulic fluid, OS-45, were separately used to test four high-temperature elastomers, Viton A, nitrile rubber, neoprene, and a fluorinated silicone, LS-53, at temperatures ranging from 190 to 300 F and at a gamma dose of 1.75×10^8 ergs g⁻¹ (C). Fluid pressures ranged from 0 to 1,000 psig. Viton A, nitrile, and LS-53 rubbers were used in O-rings and Gask-O-Seals, while the neoprene was used only in the Gask-O-Seals. There were no elastomer failures during these 200-hour tests.

A few silicone materials used as O-rings have been subjected to radiation-damage tests. Work at the Sarah Mellon Scaife Radiation Laboratory, Pittsburgh, Pennsylvania, indicated that Silastics 160 and 181 show fair resistance to radiation damage.⁽¹⁸⁾ In these tests, the O-rings were bombarded under nonfunctioning conditions (not holding a vacuum seal) in an external deuteron beam of a cyclotron. O-rings that had absorbed 2×10^9 ergs g^{-1} (C) from the deuteron beam showed little damage and held a vacuum seal after irradiation. Although they were damaged considerably, Silastics 160 and 181 held a vacuum seal after absorbing 2×10^{11} ergs g^{-1} (C). These materials cannot be used for vacuum seals after absorbing 10^{12} ergs g^{-1} (C).

Stewart and Palmer⁽⁸³⁾ investigated the use of a high-temperature rubber O-ring as a static seal in a 590 F pulse amplifier. Of the silicone rubbers considered for use in this application, Dow-Corning's S-2071 and S-675 stood out as having some promise. Tests showed the S-2071 rubber to be satisfactory for better than 100 hours at 590 F, but the rubber was found to be very unsatisfactory under the specified radiation level of 2×10^9 ergs g^{-1} (C). Wire insulated with S-2071 was exposed for 24 hours at 10^6 r/hr at 500 F. After this very short exposure to radiation, the silicone rubber insulation was badly embrittled and cracked.

Dow-Corning conducted combined temperature and radiation tests on S-675, S-2071, and S-2097 for 100 hours at 400 F and 0.1 megard hr^{-1} of gamma radiation. The S-675 rubber was the least affected by this exposure but it showed some reduction in elongation.

Although there are many characteristics in favor of the silicone rubber O-ring, the limited useful life at the required nuclear radiation levels and 590 F temperatures precludes its use where service life in the order of 100 hours or more is a requirement.

DeZeth⁽⁸⁴⁾, of Boeing Airplane Company, has tested General Electric Company's SE-551 (methyl phenyl-type silicone elastomer), SE-371 (methyl vinyl-type silicone elastomer), Viton A, a high-temperature Thiokol, and Teflon as materials for O-rings. The specimens were between 1 and 1-1/2 inches in diameter and 0.005 to 0.139 inches thick. No visible changes were observed for Viton A or SE-371 at 8.3×10^9 ergs g^{-1} (C) although the silicone materials broke when handled. Thiokol showed no visible changes at 4.2×10^9 ergs g^{-1} (C) (the highest dose at which it was tested). Teflon was completely crumbled at 8.3×10^8 ergs g^{-1} (C). It was concluded from these tests that high-temperature Thiokol and Viton A exhibit good properties after high radiation doses, while the elastomers SE-551 and SE-371 have limited use in nuclear environments. The samples, however, were not tested under service conditions, and the size of the samples was small.

Convair reported the changes in mechanical properties of a natural-rubber O-ring material irradiated while under stress.⁽⁸⁵⁾ The recipe for this stock, having a Shore A durometer hardness of 35 to 40, is given in Table A-46. Samples were irradiated while under 25 per cent compression or while held in 180-degree bend with a 5/8-inch radius at the bend. Both control and irradiated samples were held in this condition for a total of 30 days, including radiation time. The specimens, both stressed and unstressed, were irradiated to three exposure levels at ambient temperature. Mechanical properties of this rubber before and after irradiation are given in Table A-47. The compression set after irradiation is given in Table A-48.

The results of these tests show that natural rubber irradiated while under stress decreases in tensile strength and elongation to a much greater degree than does the unstressed rubber. Also, compression set of the natural-rubber vulcanizate buttons decreased by 55 per cent when the samples were irradiated while unstressed, but compression set of the O-ring segments compressed during irradiation increased from 6 per cent for the control to 80 per cent at the highest dose. At the two higher exposures the permanent set in the 180-degree bend was 100 per cent.

Newell, of Convair, offers the following explanation for these results. The predominant reaction during irradiation of natural rubber is crosslinking of the molecules. When the rubber is under compression during irradiation, the crosslinking tends to set the rubber permanently in the existing strained condition; when the rubber is irradiated unstressed, the crosslinking results in a harder and more rigid structure which tends to resist subsequent compression set.

Newell also found that the stressed samples cracked badly on the outside of the 180-degree bend where the rubber was under tension. At the two higher exposure levels, similar cracking also occurred in the compression buttons. This cracking was believed to be due to the ozone content of the atmosphere in the radiation field. O-rings irradiated in the grooves of the chamber doors did not show this cracking. This was due to the lack of contact of these O-rings with ozone on the outside of the bend, since this portion of the O-ring was in contact with the pool water.

A comparison of natural-rubber and diisocyanate polyester O-rings is presented in Table 24. (86) These results show that, at 3×10^{10} ergs g^{-1} (C), the hardness of the polyester did not change from its original value, while the natural rubber changed from 70 to 95.

The importance of seal and groove design has been the subject of a study by Trepus and co-workers at Boeing Airplane Company. (13) Rectangular, V-shaped and tapered-bottom grooves were tested using O-rings made from a Viton A compound. The temperature of the test jigs was raised, in 100-degree increments, from room temperature to 600 F and back down again with pressure checks at each temperature level. The rings were aged from 2 to 12 hours at 600 F.

Trepus found that the principal factors causing seal failure were permanent set and shrinkage of the O-ring due to the high temperature. The temperature-cycling tests indicated that the O-rings took a permanent set after prolonged exposure to high temperatures and pressures, causing slight leakage when the temperature was lowered. A relatively high squeeze on the O-rings was necessary for sealing over a wide range of temperatures to overcome the effects of permanent set of the O-ring and the difference between the thermal expansion of the seal and that of the sealing gland. In these tests V- and tapered-grooves failed to improve seal life. Data are given in Table A-49. These seals were not subjected to irradiation. The effect of groove design on service life in a radiation environment is to be studied later.

O-rings were also tested for use at cryogenic temperatures. (13) The elastomers tested were SBR, NR, CR (WRT and GN), NBR, Thiokol FA, and Philprene VP-4. None will give reliable O-ring seals at temperatures around -300 F.

Convair⁽¹⁷⁾ tested nitrile rubber and neoprene WRT O-rings containing 5 parts per hundred of an antirad (Akroflex C). The neoprene O-rings were irradiated in air and in a pressure vessel containing Oronite 8515 at 350 F and 3,000 psi for 14 hours

TABLE 24. COMPARISON OF NATURAL-RUBBER AND DIISOCYANATE
POLYESTER O-RING GASKETS UNDER IRRADIATION (86)

O-Ring	Size (a)	Before Treatment	Heated in Air 135 C, 306 Hr	Irradiated to 3×10^{10} Ergs G ⁻¹ (C)
<u>Weight Change, per cent</u>				
Natural rubber	Large	-	+0.80	+2.74
	Small	-	+1.55	+2.61
Polyester	Large	-	-1.16	-0.93
	Small	-	-1.49	-1.17
<u>Hardness, Shore A</u>				
Natural rubber	Large	68	90	95
	Small	70	90	95
Polyester	Large	72	70	77
	Small	72	71	76
<u>Density, g/cm³</u>				
Natural rubber	Large	1.226 ± 0.004	1.272	1.274
	Small	1.223	1.277	1.275
Polyester	Large	1.245	1.236	1.248
	Small	1.252	1.249	1.249

(a) Large rings, cross section = 0.008 sq in.
Small rings, cross section = 0.003 sq in.

while the nitrile rubber O-rings were irradiated in MIL-L-7808 oil at 275 F for the same length of time. Viton A with no antirads was also irradiated while immersed in Oronite 8515 fluid at 350 F and 3,000 psi for 14 hours. Radiation exposure was 1.9×10^{10} ergs g⁻¹ (C) (gamma dose) and 1.2×10^{15} n cm⁻² (E > 2.9 Mev). The neoprene and Viton A O-rings lost most of their original resilience properties during irradiation. The neoprene O-rings containing the antirad suffered 10 per cent less change in elongation than the standard compounds. For nitrile rubber there was no detectable difference.

Backup Rings

Backup rings improve the performance of O-rings at high temperatures since they prevent the O-ring from extruding out of the groove. Trepus⁽¹³⁾, investigating the radiation stability of backup rings, found that all Teflon and Teflon-filled rings were deteriorated to such an extent that they were unusable after an exposure dose of 8.39×10^9 ergs g⁻¹ (C). DC 2106 asbestos-filled silicone resin and SMR 21/V 204/SMR 21 outer (VS polymeric Chemicals, Inc.) appear to have possibilities as backup materials above irradiation levels of 8.39×10^{10} ergs g⁻¹ (C). However, they do not perform well as backup materials at lower radiation levels. Before irradiation they are extremely hard, which results in the abrasion of the O-ring against the hard sharp corners of the backup ring.

Convair⁽⁸⁷⁾ examined Epocast No. 2 and 100 Shore A nitrile rubber as backup materials for rubber surface seals. Both materials extruded and gripped the moving surface, which resulted in backup-seal destruction and O-ring damage. However, Epocast No. 2 was satisfactory as backup rings for static seals in hydraulic pump loops.

Lockheed⁽¹⁴⁾ found Viton A-asbestos backup rings satisfactory for use in a flight-control system operating at 200 F using MLO 8200 hydraulic fluid. The irradiation dose was 8.77×10^9 ergs g⁻¹ (C). In a subsequent test⁽¹⁵⁾, backup rings made of Viton A-asbestos, Teflon, and leather (used in a relief valve) gave satisfactory performance in an electrohydraulic servo loop using Oronite 8515 hydraulic fluid at a temperature of 275 F and a pressure of 3,000 psi. Irradiation dose was 1.3 to 4.9×10^9 ergs g⁻¹ (C), depending on the location of the parts in the system. The Teflon ring was brittle, but maintained a seal. Both the Teflon and Viton A-asbestos backup rings were bonded to the O-rings and could not be separated without damage when removed.

For specific applications, particularly in contact with oils, exposure doses may be increased somewhat. Teflon backup rings have been reported to operate 500 hours in a flight-control system and to withstand an exposure dose of 4.4×10^9 ergs g⁻¹ (C) (5×10^7 roentgen), of combined neutrons and gammas.⁽⁶⁰⁾ The only damage to the backup rings was a slight increase in hardness. However, Teflon slivers had broken off and were found in the pump used in the control system. The edges of the backup rings were feathered due to breaking off of these slivers.

Sealants

Below 300 F, nitrile, neoprene, and Thiokol elastomers have been used as sealants. Of these, Thiokol is the most commonly used material, particularly as fuel- and oil-tank sealants. The radiation resistance of these elastomers is shown in Table 25. Neoprene and nitrile have not been exposed in a fuel medium and the radiation resistance

TABLE 25. RADIATION STABILITY OF ELASTOMERS AND PLASTICS USED AS SEALANTS

Elastomer	Chemical Composition	Temperature Range, F	Radiation Stability Maximum Dose, ergs g ⁻¹ (C)	Reference
Viton A	Copolymer of hexafluoropropylene and vinylidene fluoride	To 450	1×10^9 (in air)	(92)
RTV Silicone				
Thiokol	Polysulfide	140	1×10^9 (in air)	(92)
Nitrile	Copolymer of acrylonitrile and butadiene	To 280	3.5×10^9 (in JP-4 fuel) 1×10^{10} (in air at room temperature)	(88) (106)
Neoprene	Polymers and copolymers of 2-chlorobutadiene	To 250	1×10^9 (in air at room temperature)	(141)

can be judged only by their radiation resistance in air, which is in the range of 1×10^{10} ergs g^{-1} (C) for moderate damage (approximately 25 per cent). Thiokol is among the poorer radiation-resistant rubbers when irradiated in air. For use above 300 F, Fluorocarbon, and silicone materials have been used as sealants.

Thiokol Sealants

Thiokol sealants were irradiated at 140 F at three different doses while immersed in JP-4 fuel. These sealants were found to be resistant to a dose of 3.5×10^9 ergs g^{-1} (C) but were unsatisfactory at 1×10^{10} ergs g^{-1} (C).⁽⁸⁸⁾ The reduction in tensile strength at the lowest radiation dose, 9.3×10^8 ergs g^{-1} (C), was of the order of 10 per cent. Elongation showed no change and hardness was reduced 50 per cent. Specimens showed no visible evidence of degradation. At 3.5×10^9 ergs g^{-1} (C), tensile strength was reduced by 25 per cent, elongation by 13 per cent, and hardness by 16 per cent. There was no visible evidence of damage at 9.9×10^9 ergs g^{-1} (C). The samples were badly pitted and swollen due to the penetration of fuel through the Buna N overcoat. The tensile strength was reduced by 68 per cent after evaporation of the fuel. Elongation was reduced 54 per cent and hardness 23 per cent.

Three Thiokol sealants, PR 1201 (HT), EC 801, and EC 1373 were irradiated by Convair to a dose of 2.5×10^9 ergs g^{-1} (C) while immersed in JP-4 fuel. Specimens of these materials, topcoated with a nitrile rubber, EC-776, were irradiated in both air and JP-4 fuel. Although some changes were noted, none of the sealants were degraded enough to seriously affect their serviceability.

Workers at Convair⁽¹⁷⁾ also irradiated three commercial Thiokol sealants, PR-1422, EC-1610, and EC-1520 in air and in JP-4 fuel. The sealants irradiated in fuel showed more reduction in tensile strength and elongation than sealants irradiated in air. Laboratory samples of Thiokol sealants which contained a high filler content (Titanox AMO or a combination of Titanox AMO and Calcene TM) were less radiation resistant than the controls when irradiated in fuel. This decreased resistance with fillers has also been noted in elastomers irradiated in fuel. The peel strengths of the commercial sealants were approximately the same whether they were irradiated in air or in JP-4 fuel. In most cases, peel-strength values did not show a great decrease until after an exposure of 10^9 ergs g^{-1} (C). At a dose of 10^{10} ergs g^{-1} (C) peel strength was extremely poor. (See Tables A-50 through A-54.)

A Thiokol-based sealant, PR-1422, maintained satisfactory tensile strength and elongation when irradiated to an exposure dose of 8.7×10^9 ergs g^{-1} (C). Postirradiation aging at 275 F for 24 hours gave satisfactory stress-strain values. This material is believed to be capable of service at 275 F for long periods of time.

Three Thiokol-based sealants, were subjected to a dose of 9.6×10^7 ergs g^{-1} (C) in a nuclear burst.⁽⁸⁹⁾ These sealants became radioactive (100 to 1,200 counts per minute) at doses of 3.5×10^7 ergs g^{-1} (C) and above.

High-Temperature Sealants

Materials used as high-temperature sealants in the range of 300 to 500 F are Viton A, Silicone LS-53, and Polymer 1F4. Elastomer 214⁽⁹⁰⁾ and the new nitrile-silicone polymer⁽⁹¹⁾ have also been recommended as sealants. Data are available for

Viton A and Silicone RTV as fill and drain sealants⁽⁹²⁾ (see Table 25). Viton A compositions were found satisfactory after gamma irradiation at approximately 1×10^9 ergs g^{-1} (C), either preceded or followed by exposure to JP-4 fuel at 450 F for 7 days. Several RTV silicone sealant compositions satisfactorily withstood exposure to approximately 1×10^9 ergs g^{-1} (C). Exposure to 1×10^{10} ergs g^{-1} (C) caused drops in elongation to values which are not acceptable in service. The radiation resistance of Viton A sealants has not been improved by antirads, although several compositions containing lead salts of potential antirads show some promise and work is being continued in this area.⁽⁹²⁾

Fluorocarbon Sealants. Seegman and co-workers at Product Research Company⁽⁹³⁾ developed a fill and drain sealant, G-59, a brush-type faying-surface sealant, a filleting sealant, and a tape, all based on Viton A (a copolymer of hexafluoropropylene and vinylidene fluoride). These were all satisfactory for use at 450 to 600 F. The G-59 fill and drain sealants, both catalysis and solution cured, were irradiated to an exposure dose of 8.7×10^9 ergs g^{-1} (C). The Viton A filleting sealant gave satisfactory tensile strengths to a dose of 8.7×10^8 ergs g^{-1} (C). After irradiation to 8.71×10^9 ergs g^{-1} (C), elongation dropped to 10 to 25 per cent. Two Viton B fill and drain sealants (dithiol cured)⁽⁹⁴⁾ were irradiated to 1×10^{10} ergs g^{-1} (C). Tensile strength increased, but elongation decreased considerably, although not to the extent of the Viton A sealants. Data for the Viton B materials are given in Table 26.

TABLE 26. TENSILE PROPERTIES OF VITON B FILL AND DRAIN SEALANTS BEFORE AND AFTER GAMMA IRRADIATION⁽⁹⁴⁾

Formulation(a)	Before Irradiation		After Irradiation at 1×10^{10} Ergs G^{-1} (C)	
	Tensile Strength, psi	Elongation, per cent	Tensile Strength, psi	Elongation, per cent
G-198-1	680	540	1840	55
G-202-1	1470	460	1530	45
(a) Reel/psi	G-198-1		G-202-1	
Viton B	100		100	
Maglite B	10		10	
Thermax	30		--	
SD Stone 120	--		20	
Durez 175	10		--	
Dibenzylamine	2		2	
MIBK	322		362	
	474		494	
Press precure before solvent dispersion	300 F/2 hr			
Cure	250 F/1 hr			
Curing System				
Hexamethylene dithiol (HMDT)	1.5			
Tri-n-amyamine (TnAA)	0.5			
MEK	13.0			
Total	15.0			

The aim of the Products Research work is to develop fuel-resistant sealants which will withstand nuclear radiation up to 10^{11} ergs g^{-1} (C) at 450 F, and cabin pressurization sealants for use up to 1500 F in a nuclear-radiation environment.⁽⁹⁵⁾ Several antirads for the Viton A formulation were tested, but did not provide any increase in radiation stability. Similar results with antirads were obtained by workers at B. F. Goodrich.⁽⁵¹⁾

Silicone Sealants. Seegman, and co-workers at Products Research Company⁽⁹³⁾ developed a channel sealant, C-37, based on reverted Silastic LS-53U which is serviceable to 450 F, and a RTV (room-temperature vulcanization) silicone pressurization sealant which is satisfactory for use at 700 F for periods of several hours, depending on the configuration and environment. These were tested for radiation stability. The reverted Silastic LS-53U (uncured fluorinated silicone) channel sealant, C-37, converted to a tough rubber at 8.7×10^7 ergs g^{-1} (C). The silicone pressurization sealant maintained satisfactory tensile and elongation properties to 8.7×10^8 ergs g^{-1} (C) exposure dose. Exposure to 1×10^{10} ergs g^{-1} (C) caused drops in elongation to values which are not acceptable in service.

Room-temperature cured and heat-cured silicone sealants were subjected to a dose of 9.6×10^7 ergs g^{-1} (C) in a nuclear bucket.⁽⁸⁹⁾ The heat-cured silicone increased in hardness, but serviceability of the sealants was not impaired in this test.

Seals and Gaskets

Materials that are used for seals and gaskets may be divided into two groups: (1) those which are satisfactory for operation up to 300 F, and (2) those for service above 300 F. In present aircraft and missiles, the operating range is above 300 F and, consequently, there is a greater interest in the radiation-resistant limits of the higher temperature resistant products that are prepared from polymers such as the fluorocarbons and the silicones.

Seals and gaskets have been found to be more radiation resistant when immersed in oil and, as a result, seals of Viton A^(60, 96), silicone⁽⁹⁷⁾, or nitrile rubber⁽⁹⁸⁾ are now believed capable of service to an exposure dose of 10^{10} ergs g^{-1} (C); whereas, on the basis of static tests in air, an exposure dose of 10^8 ergs g^{-1} (C) has been considered maximum.

Elastomers that are used as seals or gaskets below 300 F include natural rubber, SBR, Butyl, nitrile, neoprene, and polyurethanes. Plastic materials are polystyrene, polyvinyl chloride, and polyethylene. The radiation resistance of these polymers is shown in Table 27. The data given are for exposure in air only, since no information was available as to their radiation resistance immersed in oil or other fluids. Irradiation data on gaskets or sealing materials for use at 300 F has been found only for those prepared from neoprene and nitrile rubbers. This is probably because, as seals and gaskets, are resistant to oils and some fluids and therefore have been used more frequently in aircraft applications.

TABLE 27. RADIATION STABILITY OF ELASTOMERS AND PLASTICS USED
IN SEALS AND GASKETS AT TEMPERATURES BELOW 300 F

Material	Chemical Composition	Use	Temperature Range, F	Fuel and Oil Stability	Radiation Stability Maximum Dose, ergs g ⁻¹ (C) in air	Reference
<u>Elastomers</u>						
Natural rubber	Isoprene polymer	O-rings			5 x 10 ¹⁰	114
Styrene butadiene (SBR)	Copolymer of styrene and butadiene				1.5 x 10 ⁹	69
Nitrile	Copolymer of acrylo- nitrile and butadiene	O-rings, seals, gaskets, sealants	-40 to 280	Oil resistant	1 x 10 ¹⁰	106
Neoprene	Polymers and copolymers of 2-chlorobutadiene	O-rings, seals, gaskets	-40 to 250	Oil resistant	1 x 10 ⁹	141
Butyl	Copolymer of isobutylene and isoprene (0.5-4, 5%)				4 x 10 ⁸	69
Polyurethane					1 x 10 ¹¹	114
<u>Plastics</u>						
Polystyrene					1 x 10 ¹¹	104
Polyvinyl chloride					1 x 10 ¹⁰	69
Polyethylene					1 x 10 ¹¹	104
Epoxy					9.5 x 10 ¹⁰	69
Polyurethane					1 x 10 ¹¹	104

For Use Below 300 F

Morris⁽⁹⁹⁾ determined the compression set and softness of 23 vulcanizates after exposure to 8.8×10^9 ergs g^{-1} (C) (10^8 roentgens). Sulfur was used for curing all of the vulcanizates of the several styrene-butadiene and acrylonitrile-butadiene rubbers which were tested, except one of each, which were cured with dicumyl peroxide. Other rubbers were cured with the usual ingredients. All recipes, except Philprene VP-25, Viton A-HV, and the silicone rubbers, contained Philblack A (a fast-extruding furnace black) as a reinforcing filler. No filler was used in Philprene VP-25. Viton A-HV contained Thermax (a medium thermal black). Silicone W96 contained HiSil X303, a very fine silicon; the fillers in Silastic S-2048 and LS-53 were not identified. Curing conditions and filler content were adjusted so that the vulcanizates had the hardness and resistance to hot compression set of a typical O-ring seal.

Table A-55 shows the results of exposures to 8.8×10^9 ergs g^{-1} (C). The two rubbers having the best inherent resistance to gamma radiation were Adiprene C and Synpol 1500. However, some of the Adiprene C specimens were crushed after being compressed for 23 days. This effect was evident whether the specimens had been irradiated or not. This behavior indicates that Adiprene C is too brittle for use in gaskets and seals.

The specimens of Synpol 1500 were not crushed by compression. The stock cured by dicumyl peroxide had better resistance to radiation than the sulfur-cured stock, although the resistance of the latter was enhanced by compounding with an antioxidant and a plasticizer which contained benzene rings. For example, Synpol 1500 cured with sulfur and containing Thermoflex A antioxidant and dibenzyl phthalate had a high indentation and the lowest compression set (49 per cent) after a dose of 8.8×10^9 ergs g^{-1} (C) (10^8 roentgens) of any vulcanizate tested in this program. Acridine, a high-resonant-energy material, proved to be an efficient antirad for Synpol 1500; it was as beneficial as the best antioxidant, Sanctiflex GP.

According to Morris, properly compounded Synpol 1500 (or its equivalent) is considered the best rubber found to date for use in gaskets and seals where resistance to gamma radiation is required. This rubber, however, is not resistant to petroleum oils or gasoline. Where gaskets and seals with resistance to petroleum oils as well as to gamma radiation are required, Hycar 1072, an acrylonitrile-butadiene copolymer modified to contain carboxyl groups, is the best rubber to use. Its compression set was quite low (58 per cent) and its indentation was reasonably high after a dose of 8.8×10^9 ergs g^{-1} (C) (10^8 roentgens), providing the stock contained a suitable antioxidant, such as Wingstay 100. If gaskets or seals are to be used in contact with aromatic gasoline, they should be made from Hycar 1071. This is similar to Hycar 1072 except it contains more acrylonitrile. It is slightly inferior to Hycar 1072 in resistance to radiation.

Compounds containing precipitated silica as a filler show superior high-compressive-stress characteristics. Compounds with fumed silica fillers are somewhat superior in original physical properties, in resistance to confinement at high temperatures, and in compression set at temperatures above 400 F. Diatomaceous silica fillers, when used alone, furnish only moderate reinforcement to silicone rubber compounds. Di-tertiary butyl peroxide is the best of the catalysts for low compression set and may contribute slightly to improved heat resistance. The pronounced effect of heat on virtually all the properties of silicone rubber indicates a maximum temperature limitation of 500 F for their successful use in seal applications. The selection of materials must

result in a compromise of desirable properties and should be based on a careful analysis of the functional requirements of a part to determine the properties most essential to its effective performance.

The hardnesses of all the vulcanizates included in this investigation, except Genthane S, a polyurethane, were consistently increased by exposure to radiation. Thus, it appears that the compression sets of these rubbers were largely due to the formation of new cross links. Genthane S apparently experienced considerable breakage of primary valence bonds in the earlier stages of irradiation.

Harmon⁽⁵¹⁾ determined the combined effects of radiation and elevated temperatures on a packing compound based on a 60:40 Neoprene W-Neoprene WHV formulation. The results of these tests are shown in Table A-56. This compound has very poor radiation stability. This, combined with poor retention of properties at 158 F, gave a material with very low tensile strength and per cent elongation when irradiated at 158 F.

Brooks and co-workers at Convair⁽⁸⁵⁾ determined the radiation stability of several gasket materials, including cork and neoprene (Armstrong DC-100) and neoprene reinforced with compressed asbestos (Palmetto Packing No. 2915). These compounds were pliable after irradiation to 2.5×10^8 ergs g^{-1} (C) and were the best of the materials tested.

For Use Above 300 F

Elastomers which are presently used as seals at a temperature range above 300 F include the fluorocarbons, Viton A and Elastomer 214, Kel-F elastomer (copolymer of chlorotrifluoroethylene and vinylidene chloride), and the silicones. Plastics used as seals include Kel-F and Teflon. The radiation stability of these compounds is shown in Table 28. None of the materials have exceptional radiation stability when exposed in air. Of the elastomers, Kel-F shows the least resistance to radiation and becomes quite soft and tacky at doses below 6×10^8 ergs g^{-1} (C)⁽¹⁰⁰⁾. Viton A, Elastomer 214, and Polymer 1F4 are about equal in radiation resistance^(12, 100). For dynamic applications, they should not be exposed to a dose greater than 1×10^{10} ergs g^{-1} (C). For static operation, they could probably be used to somewhat higher doses. Methyl phenyl silicones show somewhat better resistance; some of them retain flexibility to 3×10^{10} ergs g^{-1} (C). The radiation stability of fluorinated Silicone LS-53 is inferior to that of the other silicones, and properties such as elongation and tensile strength deteriorate rapidly at 5×10^8 ergs g^{-1} (C).

Fluorocarbon. Because many of the fluorocarbon elastomers have been found useful as high-temperature seals in diester oils and fluids, there has been a great deal of interest in their radiation resistance. Table 28 presents the radiation resistance of these compounds when used as seals and gaskets. The most interesting factor found in irradiation studies is that many of them behave differently on irradiation in diester fluid than in air. For example, Griffin⁽¹²⁾ found that, when Viton A and Elastomer 214 were irradiated in air, they began to get soft and tacky at 6×10^8 ergs g^{-1} (C), but they survived 1×10^{10} ergs g^{-1} (C) in diester oil at 400 F with retention of rubberlike properties. In argon gas, however, an exposure to 5×10^8 ergs g^{-1} (C) at 400 F caused a 75 per cent loss in tensile strength and elongation. At 500 F, the same dose caused a complete loss of useful properties. This was more severe than in the presence of the diester oil. On the other hand, Griffin stated that Polymer 1F4 (a polymer of 1, 1-dihydroperfluorobutyl

TABLE 21. RADIATION STABILITY OF ELASTOMERS AND PLASTICS USED FOR SEALS AND GASKETS FOR OPERATION ABOVE 300 F

Material	Chemical Composition	Use	Temperature Range, F	Fuel and Oil Resistance	Radiation Stability in Listed Environment, Max. Initial Dose, ergs g^{-1} (C)	Remarks	Reference
Elastomers							
Viton A	Copolymer of hexafluoropropylene and vinylidene fluoride	O-rings, seals	-65 to 600	Diesels oils	1×10^{16} in diesel oil at 400 F 6×10^9 in air at room temperature 1×10^{10} in diesel oil at 400 F	Tensile strength decreases by 75% when exposed to $5 \times 10^8 \text{ ergs g}^{-1}$ (C) at -400 F in argon gas	12 69 12
Elastomer D14	70:30 copolymer of hexafluoropropylene and vinylidene fluoride	O-rings, seals	-65 to 600	Diesels oils, silicate ester fluids			
FF-4 (PolyFBA)	Polymer of 1,1-dihydroperfluorobutyl acrylate	Seals, gaskets	0 to 450	Diesels oils	5×10^9 in diesel oil at 400 F 1×10^{10} in air at 65 F		
Kel-F Elastomer	Copolymer of chlorotrifluoroethylene and vinylidene chloride	O-rings, seals	to 400 F	Silicate ester fluids	$< 6 \times 10^8$ in air at room temperature	Becomes soft and tacky	100
Silicones							
SE-551 (white)	Polymethylphenylsiloxane	O-rings, seals	-70 to 450		1.34×10^9 in air at room temperature as samples 5.3×10^9 in air at room temperature as samples 2×10^{11} as vacuum seal at room temperature 2×10^{11} as vacuum seal at room temperature 1×10^9 as gasket in contact with oil at 450	Broke when handled at $5.3 \times 10^9 \text{ ergs g}^{-1}$ (C)	84
SE-571	Polymethylvinylsiloxane	O-rings, seals					
Silastic 150	Polymethylsiloxane	O-rings, seals				Did not hold at $61 \times 10^{12} \text{ ergs g}^{-1}$ (C)	19
Silastic 181	Polydimethylsiloxane	O-rings, seals				Did not hold at 3.7×10^{11} ergs g^{-1} (C)	18
Silastic 16-1-4-450	Polydimethylsiloxane	Gaskets	to 450			Did not hold at $61 \times 10^{12} \text{ ergs g}^{-1}$ (C)	103
Prevision Rubber 15-70		O-rings, seals			2×10^{-1} as vacuum seal at room temperature 1.2×10^{11} as vacuum seal at room temperature	Did not hold at 2×10^{12}	13
Prevision Rubber 15-70		O-rings, seals				Did not hold at 1.4×10^{12}	15
LS-53	Polymer of methylphenylchlorosiloxane		-50 to 450	Gasoline, jet engine fuels, hydraulic fluids, engine oils	5×10^8 in air at room temperature	Resistance to oils decreases as temperature increases	170
Plastics							
Teflon	Polytetrafluoroethylene	O-rings, seals, gaskets	to 500 F	Jet turbine oil	$< 1 \times 10^3$ in air at room temperature	Crumbled at $2.3 \times 10^{12} \text{ ergs g}^{-1}$ (C); felted Teflon holds seal better than solid Teflon	34, 123
Kel-F	Polychlorotrifluoroethylene				2×10^3 in air at room temperature	Very brittle at 2.4×10^{10}	104

acrylate) retained rubberlike properties after an exposure of 1×10^{10} ergs g^{-1} (C) in 65 F air but, when exposed in the presence of 400 F diester oil, the same degree of damage occurred at 5×10^9 ergs g^{-1} (C), or at one-half the dose.

It is not certain in this case whether the presence of the oil caused an adverse or a beneficial effect. General Electric^(5,101) showed that Mil-7808 oil extended the life of Viton A in a radiation environment, as compared to irradiation in air. It has been suggested that petroleum (and perhaps other oils) may be a natural protective agent against gamma radiation by acting as a scavenger for free radicals or by providing an effective medium for energy transfer.⁽⁷⁾

Inland Testing Laboratories⁽¹⁰³⁾ found that Teflon gaskets immersed in oil at 450 F would not hold a seal when exposed to a dose of 3×10^8 ergs g^{-1} (C). Felted Teflon (Armalon), however, retained sealing properties longer than did the solid Teflon. This was attributed to the resilience of the matting rather than to an increase in the radiation stability of the Teflon fiber. However, with the particular equipment used, a light face pressure was used between the gasket and glass, and the felted Teflon acted as a wick and was not satisfactory for use in the gaskets.

Teflon and Kel-F were examined as gasket materials at the Oak Ridge National Laboratory at a maximum dose of 10^{10} ergs g^{-1} (C). Neither were found useful beyond 10^9 ergs g^{-1} (C).⁽¹⁰⁴⁾

Silicone. Silicones are not as resistant to aircraft fluids and fuels as are the fluorocarbon types. Probably for this reason, the resistance of silicones to radiation in the presence of oils and fluids has not been evaluated. However, the vacuum sealing properties of silicones have been determined during irradiation. The data obtained showed that a dimethyl silastic compound retained flexibility and maintained a vacuum seal to 2×10^{11} ergs g^{-1} (C) even though physical properties of the polymer were degraded. Another silicone rubber was reported to retain its physical properties to 10^9 ergs g^{-1} (C) when irradiated at room temperature.

In relation to the higher temperature-resistant materials, Products Research Company⁽⁷⁾ reports that there was no observed differences in deterioration of Teflon, Kel-F, and a polydimethyl siloxane when irradiated from 101 to 313 F. It would, therefore, appear that the rate of deterioration of these materials would not be affected by any temperature variation.

The investigation of silicone rubber compounds for static seals and gaskets has demonstrated the importance of tests to evaluate these materials for specific properties at environmental temperatures which simulate anticipated requirements. Some relations have been established between these properties and compound composition. Certain generalizations can be made which may serve as a guide in the selection of materials for specific applications.

Todd and Miazga, United Aircraft Corporation,⁽¹⁰⁵⁾ report that silicone compounds of 60 to 70 durometer hardness provide the lowest compression set, but harder compounds are superior for high-compressive-stress requirements.

It was found by Fainman⁽⁹⁷⁾ that the only reliable seal material in a radiation environment of 3×10^8 ergs g^{-1} (C) in contact with oil at 450 F was a silicone gasket.

The commercially available gasket used was Silastic 50-24-480. It retained its physical properties to 10^9 ergs g^{-1} (C) at room temperature. It was used in a WADC deposition tester for a total of 48 to 50 hours, where it was exposed to temperatures of 450 F and doses of 1.2×10^9 ergs g^{-1} (C).

A dimethyl silastic O-ring retained flexibility and maintained a vacuum seal to 2×10^{11} ergs g^{-1} (C), even though physical properties of the polymer were almost degraded. ⁽¹⁸⁾ In these experiments an O-ring bombardment device was made so that the O-ring would hold a vacuum seal while being rotated through a glycerine bath at a temperature of 210 C and bombarded by an electron beam. The sample was placed as close as possible (10 cm) to the beam exit on the cyclotron.

In another test, ⁽⁸⁴⁾ cupped seal rings of ceramic-filled Teflon (Duroid 5600) were completely crumbled when irradiated to 8.3×10^8 ergs g^{-1} (C). Silastics 160 and 181 were bombarded with deuterons while they were being used as a seal. ⁽¹⁸⁾ The amount of energy absorbed in the last test where a vacuum seal held was 2×10^{11} ergs g^{-1} (C) for both materials. The vacuum seal failed to hold when 1.1×10^{12} ergs g^{-1} (C) was absorbed by Silastic 160 and when 3.7×10^{11} ergs g^{-1} (C) was absorbed by Silastic 181.

Gaskets have been fabricated from Silicone Rubber 12602 and 12603. Table 29 shows that the elastomeric properties of these materials stable at radiation levels not greater than 8.8×10^8 ergs g^{-1} (C) (10^7 roentgens). However, between 8.8×10^8 and 8.8×10^9 ergs g^{-1} (C) (10^7 and 10^8 roentgens), there are considerable changes in the properties, largely due to embrittlement processes. After 8.8×10^9 ergs g^{-1} (C) (10^8 roentgens), both types of silicone rubber deteriorate to a material with approximately the same mechanical properties.

TABLE 29. HOW GAMMA RADIATION AFFECTS GASKET MATERIALS⁽¹⁰⁵⁾

Gamma Dose		Tensile Strength		Elongation		Hardness	
Roentgens	Ergs G^{-1} (C)	10 ³ PSI	% Change	%	% Change	Shore	% Change
<u>Silicone 12602</u>							
0	0	0.277		58		62	
10^4		0.245	-12	50	-14	65	4.8
10^6		0.260	-6.1	62	6.9	66	6.5
10^7		0.282	1.8	25	-57	74	19
10^8		0.151	-46	5	-91	95	53
<u>Silicone 12603</u>							
0	0	0.555		36		84	
10^4		0.540	-2.7	36	0	84	0
10^6		--	--	--	--	85	1.2
10^7		0.528	-4.9	25	-31	87	3.6
10^8		0.135	-76	5	-86	86	2.4

Brooks and co-workers⁽⁸⁵⁾ at Convair determined the radiation stability of several gasket materials, including the silicone rubbers, Silastic 50, 152, and 250

(Dow Corning), and SR-1054 and SR-1082 (Raybestos-Manhattan, Inc.). The gaskets were irradiated (1) statically at -65 F, at ambient temperatures, and at 400 F, before testing, and (2) while in use as a seal at ambient temperatures. These materials, with the exception of the glass-reinforced silicone, were pliable after irradiation to 2.5×10^8 ergs g^{-1} (C). However, they became hard and brittle after 2.6×10^9 ergs g^{-1} (C). If there had been any vibration of the joint, they probably would have failed.

Tires

Presently, aircraft tires are made of natural rubber with nylon cord. There have been some studies to determine radiation resistance of this component system. The results of irradiation of tires that had been prepared and exposed to gamma radiation at Goodyear was discussed.⁽¹⁰⁷⁾ It was found that almost no deterioration had occurred at an exposure dose of 8.4×10^9 ergs g^{-1} (C) (9.7×10^7 roentgens). The tires contained antirads.

Similar tires were irradiated at Convair, but the results were not satisfactory. The tires showed a much poorer radiation stability than those tested earlier at Goodyear. The Convair-tested tires were irradiated to 6.1×10^9 to 1×10^{10} ergs g^{-1} (C) (7×10^7 to 1.2×10^8 roentgens). After a break-in period, the four tires were tested for endurance to high-speed landings. All four failed before completing two landings.

At Goodyear the tires were tested in an environment where air was being passed over the tires constantly, and thus there was no chance for a buildup of ozone. In the Convair tests, the tires were in a confined atmosphere and Goodyear believes that ozone could have been the source of trouble. The Goodyear tires were irradiated at room temperature while the Convair tires, irradiated in the reactor, could have reached a temperature of almost 200 F. There was also a great difference in dose rate in the two tests. These are also factors which might have caused the differences in radiation stability of the tires in the two tests. The composition of the Goodyear tires was not disclosed.

Born⁽¹¹⁾ prepared four conventional tires and four other identical tires except that the latter contained 5 parts per hundred of Akroflex C (35 per cent N-N'diphenyl-p-phenylene diamine plus 65 per cent phenyl-alpha-naphthyl amine). The tires were 26 x 6.6 inch, Type VII, 14-ply rated tubeless of natural rubber and nylon cord. This is a tire currently used on military aircraft.

Tests showed that an exposure dose of 8.4×10^9 ergs g^{-1} (C) caused severe deterioration of the 26 x 6.6 inch, Type VII nylon tubeless tires. All of the irradiated tires failed by bead-to-bead blowouts, while unirradiated tires failed by ply separation and blister formation. Irradiated tires were only about one-tenth as good as nonirradiated on the basis of simulated landing tests. The tires made of rubber containing 5 parts per hundred (phr) of the antirad Akroflex C gave improved service after irradiation. The life of the tire was double compared with the irradiated tires containing no antirad.

Examination of rubber in the tire showed only a small amount of deterioration. Failure of the tire was due to poor resistance of the nylon cord to irradiation. From the tests, it has been concluded by the researchers that tires prepared from rubber containing 5 phr of Akroflex C may survive two or more actual aircraft landing after receiving a radiation exposure dose of 8.4×10^9 ergs g^{-1} (C). Significant improvement in service life may be expected with the use of radiation-resistant cord.

TABLE 3. PROPERTIES OF NYLON TIE CORDS IRRADIATED IN AIR AND IN A VACUUM(13)

Material	Exposure		Flex Life(a), hours		Tensile Strength(b)		Elongation, %	
	Dose Mrad (C)	Time Days	Irradiated in Air	Irradiated in a Vacuum	Irradiated in Air	Irradiated in a Vacuum	Irradiated in Air	Irradiated in a Vacuum
Nylon 66	0	0	4.22	6.9	26.5	26.5	21.9	21.9
	5.7×10^6	10^5	3.12	4.9	23.7	20.9	18.4	20.6
	5.7×10^6	10^6	2.48	6.3	19.7	25.0	17.0	30.4
	5.7×10^6	3×10^6	1.45	5.6	16.2	20.6	15.1	22.7
	5.7×10^6	10^7	1.21	5.7	12.7	22.1	13.4	26.3
Nylon 6	0	0	5.59	7.4	24.2	24.2	23.8	23.5
	5.7×10^6	10^5	4.90	10.2	21.1	22.4	18.8	27.9
	5.7×10^6	10^6	2.45	9.4	20.5	21.0	18.5	24.5
	5.7×10^6	3×10^6	1.85	6.9	17.9	22.4	17.1	23.3
	5.7×10^6	10^7	0.616	5.9	10.7	21.4	13.7	24.0
Nylon 66 HT (high temperature)	0	0	2.36	2.9	23.6	23.6	15.9	15.9
	5.7×10^6	10^5	2.11	3.1	22.3	23.0	14.4	21.0
	5.7×10^6	10^6	1.36	2.9	20.2	22.1	14.1	23.3
	5.7×10^6	3×10^6	0.74	3.9	17.2	20.2	11.7	16.3
	5.7×10^6	10^7	0.002	3.3	11.7	21.4	9.0	13.4

(a) Flex life represented by outer life of tie cords with a 5-pound load.

(b) Total load is given rather than pounds per square inch.

Harmon⁽¹⁹⁾ examined three types of nylon tire cords and found that, at 8.5×10^8 ergs g^{-1} (C) (10^7 rps), nylon irradiated in air lost more than 50 per cent of its original tensile strength. When irradiated in a vacuum to the same exposure dose, these nylon fibers decreased less than 15 per cent in tensile strength. Elongation of these fibers increased from 1 to 20 per cent when irradiated in a vacuum as compared with a decrease of 40 to 50 per cent when irradiated in air. Table 30 gives the stress-strain values of nylon cords irradiated in air and in a vacuum. From this table it can be seen that nylon irradiated in air shows a rapid loss of flex life with increasing radiation exposure in air. At 8.5×10^8 ergs g^{-1} (C), nylon has lost 100 per cent of its flex life. Thus, it is seen that oxygen is a strong contributor to the degradation of physical properties of nylon in the presence of radiation.

Nylon cord was used in a tire subjected to radiation. The cord did not fail at doses which were expected to deteriorate the nylon.⁽¹⁰⁸⁾ This illustrates the difficulty of estimating the stability of a material when used in a component system.

Because of its radiation stability, Dacron has been recommended for use as tire cords where radiation stability is essential. Dacron is not adversely affected by air when irradiated, as shown by the tensile and elongation strengths and the flex life of Dacron tire cords when irradiated in air and in a vacuum (see Table 31).

TABLE 31. PROPERTIES OF DACRON TIRE CORDS IRRADIATED IN AIR AND IN A VACUUM⁽¹⁹⁾

Exposure Dose		Flex Life ^(a) , hours		Tensile Strength ^(b)		Elongation, %	
ergs g^{-1} (C)	roentgens	Air	Vacuum	Air	Vacuum	Air	Vacuum
0	0	3.36	4.3	35.0	35.0	13.1	13.1
8.7×10^6	10^5	3.18	4.2	37.3	35.7	12.1	15.2
8.7×10^7	10^6	2.94	4.3	33.6	36.4	12.2	15.4
2.6×10^8	3×10^6	3.19	4.7	34.7	35.1	12.3	13.1
8.7×10^8	10^7	2.87	3.4	31.7	37.2	11.6	15.1

(a) Flex life determined by measuring rotor life of tire cords under a 5-pound load.

(b) Total load given in pounds.

In a study to determine the comparative stability of various fibers used for tire cords, Dacron with quinhydrone or quinone used as an antirad showed better resistances to radiation than the other tire-cord fibers examined.⁽¹⁰⁹⁾ Dacron, both with and without the antirad, showed the best retention of stress-strain properties after irradiation.

Transparencies

Wolock and Parker of the National Bureau of Standards⁽¹¹⁰⁾ studied the possibilities of improving the heat resistance of transparent plastics used as aircraft glazing by subjecting them to irradiation. The comonomers investigated were ethyl methacrylate, n-octyl methacrylate, methyl acrylate, isobutyl acrylate, n-octyl acrylate, methyl alpha-chloroacrylate, vinyl acetate, allyl acetate, acrylonitrile, 1,3-butadiene, methyl methacrylate, styrene, and 2,5-dichlorostyrene. The effects of irradiation on copolymers of methyl methacrylate and styrene are shown in Tables A-57 and A-58, respectively. Results indicate that the most promising polymers are the butadiene and acrylonitrile copolymers of methyl methacrylate and the acrylonitrile copolymer of styrene. Although the authors experienced some difficulty in preparing styrene-butadiene copolymers, these too appear to hold some promise. No appreciable increase in the heat resistance of these thermoplastics due to radiation-induced crosslinking was observed.

Tests were also made at ASD on acrylic- and polyester-type glazing materials (see Table 32 for description of these materials).⁽¹¹¹⁾ All of these transparent plastic materials were significantly discolored by gamma radiation. Each material underwent a characteristic sequence of color changes which varied as a function of radiation dose (see Table A-59).

The materials tested were relatively susceptible to physical and chemical changes during exposure to gamma radiation. The first observed change was that of discoloration. Optical properties of the materials were more sensitive to gamma irradiation than were the mechanical, thermal, or permanence-type properties. Table A-60 shows threshold and 25 per cent damage doses for irradiated transparent plastics. Radiosensitive properties were first detected at a dose of about 1 to 5×10^7 ergs g^{-1} (C). After doses ranging from 2×10^7 to 1×10^{10} ergs g^{-1} (C), properties were degraded by 25 per cent or more. Index of refraction, linear dimensions, and weight of the plastics were apparently unaffected. MIL-P-8257 and Sierracin 880 exhibited the best over-all radiation resistance, based on per cent change in properties with dose, while Grafit was the least stable.

RADIATION EFFECTS ON SPECIFIC POLYMERIC MATERIALS

Radiation-effects information is presently available on a variety of rubber and plastic materials. This information is at times conflicting because workers have not used identical compositions and equivalent radiation conditions in their experimental studies. With these qualifications in mind, the results of radiation studies on rubber and plastic materials are summarized. Furthermore, these studies show that the radiation resistance of elastomeric and plastic materials is dependent on (1) the composition of the compound, i. e., type of curing agents, antioxidant, fillers, and other additives utilized in their preparation, and (2) processing and curing conditions. There is some indication that, for thermosetting materials, the state of cure affects resistance of the compound to radiation. Consequently, in the discussion of data, a complete description or history of the compound and conditions of irradiation are given whenever possible. In the discussion attempts were made to arrange materials according to their radiation resistance. The materials with greater resistance are discussed first.

TABLE 32. IDENTIFICATION OF ACRYLIC- AND POLYESTER-TYPE GLAZING MATERIALS TESTED(111)

Trade Name Grade	Manufacturer	Resin	Specification	Curing or Annealing Temperature	Time at Temperature
	General Aniline & Film Corp.	Methyl alpha-chloroacrylate	--	320 F (160 C)	30 minutes
Plexiglas II	Rohm & Haas Company	Methyl methacrylate	MIL-P-5425	230 F (110 C)	150 minutes
Plexiglas 55	Ditto	Ditto	MIL-P-8184	230 F (110 C)	150 minutes
Sierracin 611	Sierracin Corp.	Polyester, proprietary information	MIL-P-8257	140 F (60 C)	360 minutes
Sierracin 880	Ditto	Ditto	--	270 F (132 C)	30 minutes
Selectron 400	Pittsburgh Plate Glass Company	Acrylic, proprietary information	--	302 F (150 C)	120 minutes
"Stretched" Plexiglas II	Rohm & Haas Company	Methyl methacrylate, mechanically oriented	--	175 F (79 C)	11 hours
"Stretched" Plexiglas 55	Rohm & Haas Company	Ditto	MIL-P-25690	175 F (79 C)	11 hours

Elastomers

In general, elastomers are less radiation resistant than are plastic materials. Among the more resistant elastomers are the polyurethane, natural, and adduct rubbers. For static operations, the polyurethane rubbers can be used up to 4.4×10^{11} ergs g^{-1} (C), the adduct rubbers to 8.7×10^{10} ergs g^{-1} (C), and natural rubber to 4×10^{10} ergs g^{-1} (C). Under dynamic conditions, these exposure limits are considerably reduced.

Most elastomers increase in hardness when irradiated. However, Butyl and Thiokol rubbers soften and become liquid with high radiation doses.

The silicone and fluorine-containing polymers are the most satisfactory rubber for use above 300 F; however, they are below average in radiation resistance. Nitrile and neoprene rubbers are the best for use below 300 F. There, radiation stability is somewhat better than that of the silicone rubbers.

Filler-loaded elastomers are more radiation resistant than is pure gum stock; carbon black appears to be the best filler for improving a compound's radiation resistance. Curing conditions are also important; a slightly undercured compound is indicated. Additional stability can also be realized through the use of antirads; however, these compounds are specific in that some are more effective with one type of polymer than with another. The best results are obtained if the antirad is used in combination with the commonly used antioxidant, phenyl beta naphthylamine.

Natural Rubber

Natural rubber is among the most radiation resistant of the elastomers thus far tested, based on the change of its over-all properties. Irradiation of natural rubber induces crosslinking. The elastic properties decrease and the hardness of the compound increases. This is similar to the effect of overvulcanization. On prolonged vulcanization, natural rubber acquires a rigidity comparable with that of glass. Sisman and Bopp⁽¹¹²⁾ found that similar results are obtained with increasing amounts of radiation.

Collins and Calkins⁽¹¹³⁾ reported that, on the basis of static data published by Bopp and Sisman⁽⁷⁶⁾, natural rubber is unaffected up to an absorbed dose of approximately 2.2×10^8 ergs g^{-1} (C). Twenty-five per cent damage is accrued for over-all properties at doses of approximately 5.5×10^9 ergs g^{-1} (C). Its tensile strength is not adversely affected until the rubber has absorbed a dose of 2.4×10^9 ergs g^{-1} (C), and elongation and set at break are not affected up to a dose of approximately 5.5×10^8 ergs g^{-1} (C). Twenty-five per cent damage is accrued with respect to tensile strength at an absorbed dose of 1.5×10^{10} ergs g^{-1} (C). Therefore, in applications where tensile strength is the primary requirement, natural rubber would probably be satisfactory up to this dose. The specific gravity of natural rubber begins to increase at an absorption of 2.4×10^{10} ergs g^{-1} (C). At a dose of 2.4×10^{11} ergs g^{-1} (C), the specific gravity of samples irradiated at Oak Ridge⁽⁷⁶⁾ increased from 1.19 to 1.24.

Harrington⁽¹¹⁴⁾ found that natural-rubber compositions possess a fair amount of flexibility after exposure to 8.7×10^{10} ergs g^{-1} (C), but will break when flexed 180 degrees after exposure to 4.3×10^{10} ergs g^{-1} (C). The hardness of natural-rubber compositions increases with increased radiation dose while elongation decreases. Tensile strength of optimum-cured compositions tends to decrease in general on irradiation up

to 4.3×10^{10} ergs g^{-1} (C), then tends to increase. Stress cracking of natural rubber may start at a relatively low exposure dose of 4.3×10^8 ergs g^{-1} (C), and becomes more severe with increasing exposure. For maximum service it is important to compound natural rubber with an antioxidant (antirad) if the composition is under stress during radiation exposure.

Convair⁽¹¹⁵⁾ irradiated a natural-rubber vulcanizate having a Shore A durometer hardness of 40 and a composition having a Shore A durometer hardness of between 70 and 80 to an exposure dose of 2.4×10^9 ergs g^{-1} (C) (6×10^{14} fast n cm^{-2} , 6×10^{13} nvt and 5×10^{16} γ cm^{-2}). The effect of radiation on the mechanical and physical properties of these materials is shown in Table A-61. Recipes are given in Table A-46. It is noted that, for the samples having the greater hardness (Shore A durometer hardness of 70 to 80), tensile strength decreased 20 per cent and elongation decreased 27 per cent. This change in tensile strength is somewhat greater than would be expected from previous data which show threshold damage as occurring after an absorbed dose of about 1.5×10^{10} ergs g^{-1} . The change in elongation is in the range which would be expected. The lack of change in compression set also agrees with previous data. However, the original compression set of these samples is much higher than that for samples previously reported. The results for the softer material (Shore A durometer hardness of 40) in which no change was found for tensile strength and elongation might also be expected if the difference in hardness is related to tightness of cure rather than to the effect of plasticizer.

Studies have been reported on the effect of radiation on natural rubber when under stress or under dynamic conditions. Tests at Goodrich⁽¹¹⁶⁾ show that natural rubber has excellent retention of Yezley resilience, has good hysteresis properties, and is resistant to change in permanent set during flexing on irradiation. Convair reported the changes in mechanical properties of a natural-rubber O-ring material irradiated while under stress.⁽³⁾ The recipe for this natural-rubber stock having a Shore A durometer hardness of 35 to 40 is given in Table A-46. Samples were irradiated while under 25 per cent compression or while held in 180 degree bend with a 5/8-inch radius at the bend. Both control and irradiated samples were held in this condition for a total of 30 days, including radiation time. The specimens, both stressed and unstressed, were irradiated to three exposure levels at ambient temperature. Mechanical properties of this rubber before and after irradiation are given in Table A-47. The compression-set buttons from the same formulation were irradiated unstressed. The compression set of this material after irradiation is given in Table A-48.

The results of these tests show that natural rubber irradiated while under stress decreases in tensile strength and elongation to a much greater degree than the unstressed rubber. Also, compression set of the natural-rubber-vulcanizate buttons decreased by 55 per cent when the samples were irradiated while unstressed, but compression set of the O-ring segments compressed during irradiation increased from 6 per cent for the control to 80 per cent at the highest dose. At the two higher exposures the permanent set in the 180 degree bend was 100 per cent.

Newell, of Convair Aircraft Corporation, offers the following explanation for these results. The predominant reaction during irradiation of natural rubber is crosslinking of the molecules. When the rubber is under compression during irradiation, the crosslinking tends to set the rubber permanently in the existing strained condition; when the rubber is irradiated unstressed, the crosslinking results in a harder and more rigid structure which tends to resist subsequent compression set.

Newell also found that the stressed samples cracked badly on the outside of the 180 degree bend where the rubber was under tension. At the two higher exposure levels, similar cracking also occurred in the compression buttons. This cracking was believed to be due to the ozone content of the atmosphere in the radiation field. O-rings irradiated in the grooves of the chamber doors did not show this cracking. This was due to the lack of contact of these O-rings with ozone on the outside of the bend, since this portion of the O-ring was in contact with the pool water.

In a second study on the effect of irradiation on stressed rubber, Shelberg and Gevantman from the U. S. Naval Radiological Defense Laboratory determined the effect of radiation on stressed natural rubber. (117, 118) Their approach was to irradiate natural rubber that was stretched 400 to 500 per cent and follow the changes in crystallinity by X-ray diffraction measurements. They found that stretched rubber is extremely sensitive to radiation damage, which manifests itself by stress relaxation and, finally, rupture. The changes in stress relaxation result in changes in X-ray diffraction intensity and those changes can be determined without damage to the samples. Also, the total irradiation times until samples ruptured give an indication of radiation stability.

Shelberg and Gevantman also irradiated stretched specimens prepared from natural latex and solid pale crepe. These rubbers differed in additives and cure and were used to give a comparison of the influence of composition and fabrication on radiation-induced crystallinity changes. Their formulations are given in Table A-62. The latex specimens were a commercial item compounded and cured for great strength, while the pale-crepe samples were sparingly compounded and cured, but capable of being highly stressed without relaxation. The latex rubber was stronger and more extensible than the milled pale crepe and contained an efficient natural antioxidant.

One latex and three pale-crepe samples were irradiated while stretched 500 per cent in a nitrogen atmosphere and at a temperature of 78 F. Irradiation was by means of X-rays at an absorbed dose rate of 2.1×10^7 ergs g⁻¹ hr⁻¹. The time for rupture and the absorbed doses are shown in Table 33. The latex rubber was more radiation resistant than the crepe, and both lost physical properties at 10^8 to 10^9 ergs g⁻¹ absorbed dose.

TABLE 33. TIME AND X-RADIATION DOSE FOR RUPTURE OF NATURAL RUBBER SAMPLES STRETCHED 500 PER CENT (119)

Rubber	Time for Rupture, hr	Absorbed Dose, ergs g ⁻¹ (a)
Latex	68.5	1.4×10^9
Pale crepe	10.0	2.1×10^8
	8.5	1.8×10^8
	8.9	1.9×10^8
Average for Pale Crepe	9.1	1.9×10^8

(a) Absorbed dose rate = 2.1×10^7 ergs g⁻¹ hr⁻¹.

Bopp and Sisman⁽⁷⁶⁾ showed that natural rubber stretched 300 per cent lost crystallinity at an exposure dose of 8.7×10^8 ergs g⁻¹, which is in agreement with the Shelberg results. On the other hand, these doses of 10^8 to 10^9 ergs g⁻¹ (C) cannot

produce detectable physical-mechanical changes in unstretched rubber. Thus it can be seen that stretched natural rubber is less resistant to radiation than the unstretched rubber.

In another stress-relaxation study, Tobolsky and Mercurie of Princeton University determined that oxidative chain scission at temperatures of 176 F and 266 F is independent of the degree of crosslinking in radiation-vulcanized natural rubber.⁽¹¹⁹⁾ Scission occurs randomly along polyisoprene chains and not specifically at crosslinked sites.

Natural rubber has been evaluated for use in aircraft tires and particularly in the functional use of antirads. With regard to use in tires, it has been found that natural rubber containing an antirad in a tire tread is not affected greatly on exposure to approximately 10^8 ergs g^{-1} (C).⁽¹¹⁾ Detailed results on the tire tests are presented in the section on tire components. Most of the studies with natural rubber have been on the evaluation of different antirads. This work is carried on by J. W. Born and co-workers at The B. F. Goodrich Company.⁽¹¹⁾ In their investigations, they have evaluated over 100 different types of materials for antirad properties. N-phenyl-N'-cyclohexyl-p-phenylenediamine extended the life of natural rubber by a factor of 10. More recent work by these researchers indicated that this effect is obtained through a combination of the above antirads and beta-naphthyl amine.

Bauman⁽¹²⁰⁾ measured the effect of antirads on the crosslink yields in black-loaded natural-rubber stocks during gamma irradiation (6.4×10^6 ergs g^{-1} hr^{-1}) (7.3×10^4 r hr^{-1}). The crosslink yields were determined by swelling techniques. Antirads decrease the crosslink yields if oxygen is absent. Oxygen alone effectively decreases crosslink yields. In the presence of oxygen some antirads further decrease crosslink yields, while others increase crosslink yields by their presence. These results may be explained in terms of competitive reactions between R radicals, the antirad, and oxygen. Evaluation of the ratios of crosslink yields and scission yields indicate that most of the scission is temporary in nature, the chain breaks being reformed rapidly.

Polyurethane Rubber

Harrington's studies⁽¹⁰⁰⁾ indicate that these elastomers are capable of giving satisfactory service to at least 8.7×10^{10} ergs g^{-1} (C). The urethane elastomers are not affected up to 8.7×10^8 ergs g^{-1} (C), but are damaged by about 25 per cent at about 4.3×10^9 ergs g^{-1} (C). The most interesting property is hardness, which remains relatively unaffected even at 8.7×10^{10} ergs g^{-1} (C). The elastomers are resistant to stress cracking and retain a great amount of flexibility and physical strength at 8.7×10^{10} ergs g^{-1} (C). At this exposure dose, compositions can be prepared that will bend 180 degrees without cracking. The results are given in Table 34.

This type of elastomer tends to decrease in both tensile strength and elongation upon exposure to radiation. In general, it tends to soften up to exposure doses of 4.3×10^{10} ergs g^{-1} (C), and then becomes increasingly harder. Compounding ingredients appear to have little effect on radiation resistance for most types. The curing system may be a factor, but further work is necessary to establish this.

Polyurethane rubber has been reported previously as being equal to or better than natural rubber with respect to radiation resistance. Harrington reported that

TABLE 34. EFFECTS OF GAMMA RADIATION ON THE PROPERTIES OF
HEAT-RESISTANT ISOCYANATE-URETHANE ELASTOMERS⁽¹⁰⁰⁾

Materials	Exposure Dose		Initial Properties and Per Cent Change					Remarks
	ergs g ⁻¹	roentgen	Hardness		Elongation		Tensile Strength	
	C	x 10 ⁻⁶	Shore A	Δ%	Per Cent	Δ%	Psi	Δ%
Adiprene								
C-1	0	0	62		530		4300	Black
	4.4 x 10 ⁸	5	-1.5		-10.4		(a)	
	8.7 x 10 ⁸	10	-2.9		-13.2		(a)	
	4.4 x 10 ⁹	50	-1.5		-40.6		-30.4	
	8.7 x 10 ⁹	100	-12.9		-57.6		-53.3	
	2.6 x 10 ¹⁰	300	-1.5		-74.5		-75.7	
	4.4 x 10 ¹⁰	500	17.3		-83.4		-80.1	
	8.7 x 10 ¹⁰	1000	15.9		-87.7		-80.4	
Adiprene								
C-2	0	0	75		360		3800	Black
	4.4 x 10 ⁸	5	-2.5		-6.9		(a)	
	8.7 x 10 ⁸	10	-2.5		-4.2		(a)	
	4.4 x 10 ⁹	50	-1.3		-1.5		-15.1	
	8.7 x 10 ⁹	100	-3.8		-30.5		-39.3	
	1.3 x 10 ¹⁰	150	0.0		-55.5		-46.9	
	2.6 x 10 ¹⁰	300	0.0		-74.2		-62.3	
	4.4 x 10 ¹⁰	500	5.1		-81.1		-72.2	
	8.7 x 10 ¹⁰	1000	11.4		-84.7		-67.9	(b)
Adiprene								
C-3	0	0	69		595		4400	Black
	4.4 x 10 ⁸	5	1.4		3.2		(a)	
	8.7 x 10 ⁸	10	1.4		-6.0		(a)	
	4.4 x 10 ⁹	50	-6.0		-17.8		-37.5	
	8.7 x 10 ⁹	100	-7.2		-30.4		-50.4	
	1.3 x 10 ¹⁰	150	-6.0		-48.0		-58.4	
	2.6 x 10 ¹⁰	300	-1.5		-67.3		-66.4	
	4.4 x 10 ¹⁰	500	1.5		-81.5		-75.9	
	8.7 x 10 ¹⁰	1000	14.5		-87.0		-80.9	
Adiprene								
C-4	0	0	68		445		3445	Black
	8.7 x 10 ⁹	100	27.9		-83.2		-59.1	(c)
Chemigum								
XSL	0	0	69		690		4000	Black
	5.2 x 10 ⁸	6	-2.9		0.0		-5.9	
	8.7 x 10 ⁸	10	-9.0		-12.1		-25.2	
	4.4 x 10 ⁹	50	-17.4		-31.9		-68.0	
	8.7 x 10 ⁹	100	-20.3		-58.0		-79.5	(c)
	2.6 x 10 ¹⁰	300	-14.5		-22.8		-86.7	(d)

TABLE 34. (Continued)

Materials	Exposure Dose		Initial Properties and Per Cent Change					Remarks
	ergs g ⁻¹	roentgen	Hardness		Elongation		Tensile Strength	
	(C)	x 10 ⁻⁶	Shore A	Δ%	Per Cent	Δ%	Psi	
PR 631-70	0	0	77		540		3170	Black
	4.4 x 10 ⁸	5		-1.3		-2.2		-4.1
	8.7 x 10 ⁸	10		1.3		-2.2		-1.1
	4.4 x 10 ⁹	50		0.0		-20.7		-22.1
	8.7 x 10 ⁹	100		-2.6		-30.2		-33.9
	2.6 x 10 ¹⁰	300		-5.2		-56.6		-58.5
	4.4 x 10 ¹⁰	500		-2.6		-69.6		-65.1
Disogrin DSA 6865	0	0	77		700		6500	Tan
	4.4 x 10 ⁸	5		1.3		2.6		(a)
	8.7 x 10 ⁸	10		-1.3		5.0		(a)
	4.4 x 10 ⁹	50		0.0		-44.3		-52.5 (c)
	8.7 x 10 ⁹	100		5.2		-68.1		-76.4
	2.6 x 10 ¹⁰	300		9.1		-95.0		-86.7
	4.4 x 10 ¹⁰	500		10.4		-96.4		-90.3
	8.7 x 10 ¹⁰	1000		20.8		-95.7		-89.9
Disogrin DSA 7560	0	0	80		650		5000	Brown
	4.4 x 10 ⁸	5		-2.5		-13.1		(a)
	8.7 x 10 ⁸	10		-5.0		-19.2		(a)
	4.4 x 10 ⁹	50		-8.0		-48.2		-46.8
	8.7 x 10 ⁹	67		-3.8		-49.5		-68.7
	8.7 x 10 ⁹	100		-2.5		-60.7		-81.2
	1.3 x 10 ¹⁰	150		-2.5		-83.8		-87.1 (c)
	2.6 x 10 ¹⁰	300		2.5		-92.3		-91.6 (c)

(a) Exceeded capacity of tensile tester (tensile strength greater than 4000 psi).

(b) Broke when bent 180 degrees.

(c) Slightly tacky.

(d) Soft and tacky.

(e) Dark brown.

elastomers were capable of giving satisfactory service to 8.7×10^{10} ergs g^{-1} (C).⁽¹²¹⁾ Schollenberger at The B. F. Goodrich Co. recently completed a study on polyurethanes⁽¹²²⁾ and concluded that limited dynamic applications might be practical after an exposure of 1.7×10^{11} ergs g^{-1} (C) and static applications might be feasible after exposure to 4.4×10^{11} or 8.7×10^{11} ergs g^{-1} (C). However, at the latter dose, the material has degraded to such an extent that it is very weak and brittle. Mechanical properties of three Estane elastomers (The B. F. Goodrich Co.) are given in Table A-63 at three radiation exposure doses.

Schollenberger found that samples which became wet showed poor radiation stability. Water leaked into the aluminum canister containing the samples being irradiated to 1.7×10^{11} ergs g^{-1} (C). It may be noted in Table A-63 that tensile strengths of all three polyurethanes exposed to this dose are considerably lower than those of the samples exposed to the next higher dose [4.4×10^{11} ergs g^{-1} (C)]. This would be expected since polyurethanes are moisture sensitive.

He also found that the presence of benzene-ring structures in the diisocyanate coupling agents improved the radiation stability of the polyurethanes. Among the diisocyanate chain couplers studied, the order of their ability to improve the radiation resistance of the polyurethanes was found to be: p-phenylene diisocyanate \approx diphenyl methane-4,4' diisocyanate $>$ m-phenylene diisocyanate $>$ 2,4-toluylene diisocyanate. For example, polyurethanes containing a p-phenylene nucleus in the diisocyanate coupling agent and a branched or long-chain-glycol chain extender (in place of butanediol 1, 4) had improved radiation resistance. Estane VC containing 32 per cent bound diphenylmethane p,p'-diisocyanate had better stability than variations of the material containing less than 24 per cent or more than 36 per cent of this coupling agent.

A high aromatic content in the polyester "backbone" component, as in polytriethylene phthalate, appears to enhance the gamma-radiation resistance of derived polyurethanes from the standpoint of retention of both stress-strain and solution properties. However, on the basis of Schollenberger's work, a high aromatic content introduced by means of the glycol chain-extending component appears to enhance radiation resistance to a lesser degree. This is of particular interest to those studying the radiation stabilities of various organic groups. No reason for the lack of improvement in the radiation resistance of the polyurethanes containing aromatic glycol components has been given. Schollenberger also found that polyurethanes based on polyesters were more radiation resistant than those based on polyethers.⁽¹²²⁾

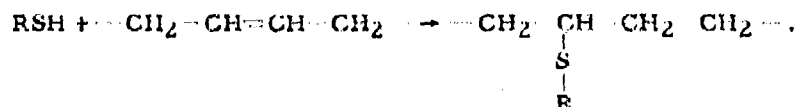
The polymers are reported to absorb oxygen during gamma irradiation. This has also been noted in ultraviolet-radiation exposures. Ordinarily, oxygen is believed to react with free radicals formed by chain scission and inhibit crosslinking. However, for polyurethanes this does not appear to be true as it does not result in degradation of properties. The aromatic composition and structure of the polyurethanes promote "end-linking", that is, the chain ends recombine to form crosslinks. Thus physical properties do not deteriorate.

A comparison of natural-rubber and diisocyanate polyester O-rings is presented in Table 24.⁽⁸⁸⁾ Results show that, at 3×10^{10} ergs g^{-1} (C), the hardness of the polyester did not change from its original value, while the natural rubber changed from 70 to 95.

According to Pestaner and Gevantman⁽¹²³⁾, a quick and useful method for measuring the radiation damage in polyurethane elastomers is to use the relationship between the extent of crosslinking and the degree of swelling in a solvent. A linear relationship was found between radiation dose and crosslinking using three different solvents. Changes in crosslinking was observable for doses as low as 1×10^8 ergs g^{-1} (C) (10^6 rads).

Adduct Rubbers

Adduct rubbers, manufactured by The Goodyear Tire and Rubber Co., are prepared by reacting diene rubbers such as polybutadiene, isoprene, etc., with a low-molecular-weight alkyl mercaptan. A highly simplified representation of a complex set of chain reactions is given by R. M. Pierson⁽¹²⁴⁾ as:



The reaction is generally carried out in latex form.

Meyer⁽¹²⁵⁾ prepared a butadiene adduct polymer 89 per cent saturated with methyl mercaptan which showed a high resistance to an exposure dose of 8.5×10^9 ergs g^{-1} (C), retaining 60 per cent of its elongation. Results for a natural rubber, neoprene, and the adduct polymer are given in Table 35. Meyer feels, on the basis of this work, that the adduct rubber makes this class of elastomers look extremely promising for uses with radiation exposure. It is possible that the greater degree of saturation may account for some of the increased radiation stability. In regard to determining the effect of the mercaptan molecule, it would be interesting to compare the radiation stability of a hydrogenated butadiene with a butadiene rubber.

In a later work Meyer, et al.,⁽¹²⁶⁾ determined the radiation resistance of adduct rubber at various exposure levels and over a temperature range of -120 to $+200$ F. Natural rubber was used as the control since it has been reported to have a longer useful life than others when exposed to gamma radiation. Data for both rubbers are presented in Table 36.

Less data were obtained on the 95 per cent saturated adduct. However, the measurements that were made indicated that it deteriorated at a somewhat lower rate than the 88 per cent saturated adduct. Both the 88 and 95 per cent saturated adducts exhibited much greater resistance to degradation by gamma irradiation than did natural rubber. The 95 per cent adduct appears to match resin-cured Butyl up to about 5 days' air-oven aging at 300 F, and all the adducts studied show better aging than neoprene at this temperature. At 500 to 600 F, the adducts appear far superior to both resin-cured Butyl and neoprene. In addition, the 95 per cent adduct exhibited a stability that was many times better than that of either Butyl 218 or neoprene upon exposure to ozone.

Harrington⁽¹²⁷⁾ investigated an 86 per cent and a 92 per cent methyl mercaptan adduct of polybutadiene, and a 65 per cent methyl mercaptan adduct of a 67/33 butadiene-acrylonitrile rubber. He found the adduct rubbers to be among the better elastomers with respect to radiation stability. The nitrile adduct was less stable than the butadiene adduct rubbers, but was more stable than the corresponding nitrile rubber. The change

TABLE 35. COMPARISON OF RADIATION STABILITY OF GOODYEAR ADDUCT, NEOPRENE GN, AND NATURAL RUBBERS⁽¹²⁵⁾

Elastomer	Adduct	Neoprene GN	Natural rubber
Total Pigment, parts	55	26	33
Tensile Strength, psi			
Original	1800	2900	3650
After 4.2×10^8 ergs g^{-1} (C)	1925	2650	2975
After 8.5×10^9 ergs g^{-1} (C)	2550	500	625
Elongation at Break, per cent			
Original	580	900	605
After 4.2×10^8 ergs g^{-1} (C)	550	835	525
After 8.5×10^9 ergs g^{-1} (C)	350	120	140
300% Modulus, psi			
Original	1000	350	950
After 4.2×10^8 ergs g^{-1} (C)	1150	375	1000
After 8.5×10^9 ergs g^{-1} (C)	2325	--	--

TABLE 36. EFFECT OF GAMMA RADIATION ON ADDUCT AND NATURAL RUBBER AT VARIOUS TEMPERATURES⁽¹²⁶⁾

Compound	Exposure		Tensile/Elongation, per cent retained at indicated temperature		
	ergs g^{-1} (C)	megareps	-120 F	75 F	+200 F
Adduct (88% saturated)	3.39×10^9	40	105/85	100/80	100/75
	8.46×10^9	100	100/45	85/55	90/55
	1.69×10^{10}	200	--	--	80/40
Natural rubber	3.39×10^9	40	80/90	65/85	20/35
	8.46×10^9	100	55/50	50/40	6/17

in the nitrile adduct rubber due to irradiation followed the same pattern as those of the corresponding nitrile rubber at low and intermediate exposures. However, it did not increase in tensile strength at high radiation exposures like the nitrile rubbers, but continued to decrease. Recipes for the adduct rubbers tested are given in Appendix A, Table A-64, while the changes in mechanical properties are shown in Table A-65. Figure 12 shows the changes for the 92 per cent saturated methyl mercaptan adduct of butadiene.

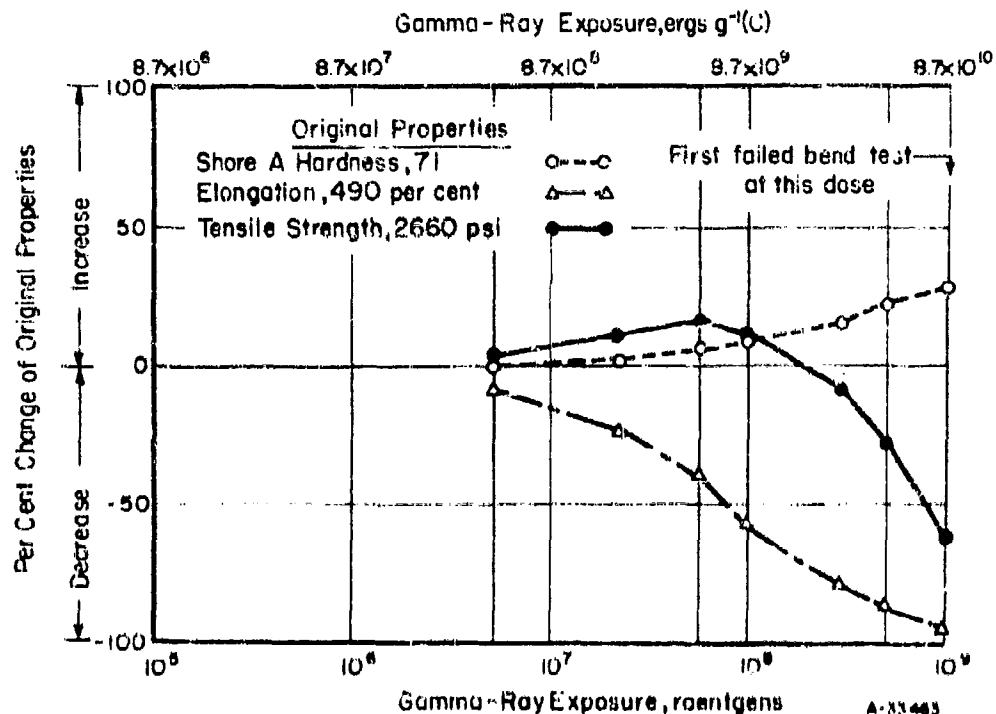


FIGURE 12. MECHANICAL-PROPERTY CHANGES IN A 92 PER CENT SATURATED METHYL MERCAPTAN ADDUCT RUBBER EXPOSED TO GAMMA RADIATION IN AIR AT 77°F AND NORMAL ATMOSPHERIC PRESSURE(127)

Styrene-Butadiene Rubber, SBR (GR-S)

Styrene-butadiene rubber (SBR), commonly called GR-S or tire rubber, resists radiation better than most of the common synthetic rubbers, but it is not equal to natural rubber in radiation resistance. These polymers deteriorate primarily by a cross-linking mechanism. Consequently, they tend to harden on irradiation.

It has been shown by Delman and co-workers⁽¹²⁸⁾ that the radiation-induced main-chain or crosslinking reaction of SBR in solution proceed by a random mechanism. Although the end chemical effects would apparently be different, vulcanizates of SBR treated in the solid state should also be expected to be randomly attacked by high-energy radiation. In a random-type degradation reaction, all molecular weight species of a polymer are equally susceptible to radiation damage. It seems highly improbable that

the radiation stability of SBR could be improved, therefore, by fractionation procedures. On the other hand, it is quite feasible that the attack of SBR elastomers can be inhibited to some extent by introducing into the backbone or side chains, structures, such as phenyl rings, which can readily absorb and dissipate radiation energy without itself or neighboring groups being appreciably affected. The literature⁽¹²⁹⁾ indicates that there is a limit to the number of phenyl rings which can influence the radiation stability of the polymer molecule. Addition of phenyl rings above this limiting concentration would not necessarily produce a corresponding increase in the resistance of the elastomer to attack by gamma radiation.

Work by Stanley and Delman⁽¹³⁰⁾ indicates the relative stability of the principal structural linkages in SBR polymer. The cis-1,2 butadiene groups containing the external double bond are more rapidly degraded by ionizing radiation than are the internal trans-1,4 butadiene units. The phenyl concentration in the SBR chains is only moderately affected by irradiation, because of the stabilizing influence of the phenyl ring in the structure. In the radiation degradation process, environmental factors, such as the presence of small amounts of oxygen in the system, are important and must be taken into account.

Threshold damage is reached at 2×10^8 ergs g^{-1} (C), and 25 per cent damage is accrued at 1×10^9 ergs g^{-1} (C). Tensile strength changes less readily than that of natural rubber. According to Bopp and Sisman⁽⁷⁶⁾, the tensile strength of SBR does not decrease by 25 per cent until it has absorbed a dosage of approximately 3×10^{10} ergs g^{-1} (C), as compared with a dosage of 1.5×10^{10} ergs g^{-1} (C) for natural rubber. Although its tensile strength changes less readily than for natural rubber, over-all, it is not equivalent to natural rubber in resistance.⁽⁶⁹⁾ Other properties, such as elongation, set at break, and compression set, decreased by 25 per cent at a dosage of 1.5×10^9 ergs g^{-1} (C).

Studies by John W. Born⁽¹³¹⁾ indicate that the stability of styrene-butadiene polymers to radiation improves as the styrene content is increased. Goodrich⁽¹³²⁾ tested both hot GR-S (polymerized at 122 F or higher) and cold GR-S (polymerized at 41 F) and found the rate of change of properties under irradiation to be about the same for both types of rubbers. The initial physical properties of the cold type are superior to those of the hot type, and this superiority is evident after irradiation.

Data published by Harrington⁽¹³³⁾ show that SBR rubber can be exposed to 8.7×10^{10} ergs g^{-1} (C) without becoming stiff or brittle. However, they will tend to break if bent 180 degrees. The tensile strengths may change differently for different compositions. In some compositions, there is no change; in some, tensile strength decreases only slightly with a low exposure dose and then decreases more rapidly with increased exposure doses; and in others tensile strength continuously increases. Hardness increases, while elongation decreases with continued exposure. All three properties are very little affected during exposure to 8.7×10^8 ergs g^{-1} (C). These elastomers show evidence of stress cracking at exposure doses of 4.3×10^9 ergs g^{-1} (C) and higher, and must be compounded with antioxidants for maximum service under stress.

A comparison of styrene butadiene rubber having a Shore A durometer hardness of 40 with one having a hardness of 70 to 80⁽¹¹⁵⁾ showed that the rubber having the lower hardness decreased in tensile strength when irradiated to an exposure dose of 2.4×10^9 ergs g^{-1} (C) (6×10^{14} fast n cm^{-2} , 6×10^{13} nv γ , and 5×10^{16} γ cm^{-2}), while the harder material increased in tensile strength. This decrease in the softer material

is somewhat surprising and may be due to the presence of a plasticizer. The composition and cure of this material were not given. The stock with a hardness of 70 to 80 showed the expected good radiation stability at the exposure dose of 2.4×10^9 ergs g^{-1} (C). Test results on the effects of radiation on the mechanical properties for these SBR rubbers are given in Table A-66.

The results of some combined environmental tests on SBR rubber are discussed in a previous section of this report entitled Elastomers. Data on room-temperature compression set are given in Table 12.

The SBR polymer can be improved, with respect to stability, by the addition of an antirad. Two of the better antirads for this rubber are Akroflex C and alpha-naphthylamine. (131) With Akroflex C, an SBR insulation compound changes to 50 per cent set on exposure to 1.39×10^9 ergs g^{-1} (C), as compared with 0.70×10^9 ergs g^{-1} (C) for a control containing no antirad. Also, the control lost approximately 60 per cent of its elongation at 0.80×10^9 ergs g^{-1} (C), as compared to 45 per cent for the composition containing Akroflex C at 1.26×10^9 ergs g^{-1} (C). (132)

Goodrich (132) also reports that the addition of Hycar HH, a brominated Butyl rubber which is more compatible than ordinary Butyl rubber, to SBR (GR-S) delays radiation damage. The Hycar HH-styrene-butadiene gum stock required ten times the radiation dosage to effect the same change as that produced in the pure gum SBR stock. However, the addition of Hycar HH to a carbon black-reinforced compound did not improve its radiation resistance.

Recent work at Goodrich (134) indicated that oil-extended SBR containing 25 phr of aromatic processing oil (APO) was more radiation-resistant than regular SBR. Pursuing this idea further, high viscosity SBR was extended with the following hydraulic materials recommended by WADD for their radiation resistance: 1,4-diphenoxybenzene (DPB), 1-(p-(α -cumylphenoxy)-4 phenoxy benzene (CPPB), and alkyl diphenyl ether (C₁₄-C₁₆) (ADPE).

Table 37 summarizes the radiation resistance of these different polymers on the basis of the dose required for 50 per cent compression set (Dg), and the radiation-induced compression set at 5.23×10^9 ergs g^{-1} (C) (SD).

From Table 37 it is seen that the oil-extended polymers are more resistant to radiation-induced compression set than is the control "cold" polymer. Perhaps other radiation-resistant oils which possess good antirad properties could be developed for extending SBR and further increasing its radiation resistance.

Butadiene Rubber

The available information suggests that butadiene rubber is somewhat less stable when exposed to radiation than is SBR. Work by Born (131) indicates that it crosslinks more readily when exposed to radiation than does SBR.

Studies by Grace, Davis, Hunt, and Isley (135) show that mass polymerized polybutadiene containing 50 phr of an HAF black is about equivalent to SBR rubber in resistance to radiation. A comparison of a natural rubber, SBR, and polybutadiene with radiation is presented in Table 38.

TABLE 37. COMPRESSION SET OF VARIOUS ELASTOMERIC COMPOUNDS AFTER IRRADIATION (134)

Compound(a)	$D_S^{(b)}$ $10^9 \text{ ergs g}^{-1} \text{ (C)}$	$S_D^{(c)}$, per cent
SBR, Type 1500	2.23	
Control	2.23	71
20 phr ADPE	2.35	67
25 phr APO	2.61	67
25 phr CPPB	3.09	63
25 phr DPB	3.13	62
Natural rubber	1.35	79
Cis-polybutadiene	0.39	90

(a) ADPE = Alkyl diphenyl ether (C₁₄-C₁₆)

APO = Aromatic processing oil

CPPB = 1-(p-tert-butyl phenoxy)-4-phenoxy benzene

DPB = 1,4-diphenoxy benzene.

(b) D_S = Dose required for 50 per cent compression set.(c) S_D = Radiation-induced compression set at $5.23 \times 10^9 \text{ ergs g}^{-1}$ (C).

TABLE 38. PHYSICAL PROPERTIES OF NATURAL, STYRENE-BUTADIENE, AND POLYBUTADIENE ELASTOMERS BEFORE AND AFTER IRRADIATION (135)

Polymer	Original Properties			Properties After Irradiation to $1.7 \times 10^{10} \text{ Ergs G}^{-1} \text{ (C)}$		
	Tensile Strength,	Elonga- tion,	Hardness,	Tensile Strength,	Elonga- tion,	Hardness,
	psi	%	Shore A	psi	%	Shore A
Natural + 50 parts HAF	3900	665	66	2935	350	76
SBR + 50 parts HAF	3125	600	64	2465	185	82
Mass polybutadiene + 50 parts HAF	2380	525	58	1665	165	78

Cis-polybutadiene has poorer resistance to compression set during irradiation than natural rubber. (See Table 37.) Its resistance is more like that of the halogenated polymers or Hycar 4021. With a property as radiation-sensitive as compression set it is not unexpected that changes of any kind in the polymer system, e. g., cis to trans isomerization, would render the vulcanizate less resistant to radiation damage on the basis of this measurement.

Vinylpyridine Elastomers

In general, the vinylpyridine elastomers⁽¹¹⁴⁾ are quite resistant to effects of radiation. Carbon-black loaded stock exhibited very little change in tensile strength until exposure to 4.3×10^9 ergs g^{-1} (C). This stability is probably due to the pyridine ring.

The hardness of this type polymer increased with increased radiation, changing by 25 per cent at 2.6 to 4.3×10^{10} ergs g^{-1} (C). The elongation decreases rather rapidly and loses more than 25 per cent between the levels of 4.3×10^8 and 4.3×10^9 ergs g^{-1} (C). At 4.3×10^{10} ergs g^{-1} (C), as much as 50 per cent of the tensile strength may be lost (see Table 39). Specimens tested up to 8.7×10^9 ergs g^{-1} (C) did not stress crack. Fillers appear to have an effect on stability. Carbon-black filled stocks exhibited very little change in tensile strength until exposure to about 4.3×10^9 ergs g^{-1} (C). For silica-loaded stocks, the tensile strength was reduced substantially at low exposure doses [$< 5 \times 10^8$ ergs g^{-1} (C)], remained about the same at intermediate doses [5×10^8 to 10^{10} ergs g^{-1} (C)], and increased at higher doses [$> 10^{10}$ ergs g^{-1} (C)].

Acrylonitrile Rubber

Nitrile rubbers (butadiene-acrylonitrile copolymers) have excellent oil resistance and good heat resistance (up to 400 F). For this reason they have found extensive use in aircraft parts.

The most common nitrile rubbers commercially available contain approximately 20, 25, 35, and 45 per cent acrylonitrile. The oil resistance improves with the increasing content of acrylonitrile but, at the same time, the freezing point also rises. Data indicate that, in general, acrylonitrile rubbers are about average with respect to radiation stability. Both crosslinking and chain cleavage occur at low and intermediate exposure doses, chain cleavage predominating when tensile strength decreases and crosslinking predominating when it increases. At higher exposure doses, crosslinking is very predominant.

The effect of the acrylonitrile content in the various nitrile-rubber compounds is not too pronounced. Probably the most significant effect of increase in nitrile content is on tensile strength. The original tensile strength appears to be progressively lowered by radiation as the acrylonitrile content is reduced. Although the effect on hardness is not so pronounced as that on tensile strength, hardness appears to increase slightly with increasing radiation exposure as the acrylonitrile content is reduced. Flexibility and minimum change in properties of the higher-acrylonitrile-content compounds show them to be slightly superior in radiation resistance.

TABLE 39. EFFECT OF RADIATION ON PHYSICAL PROPERTIES OF

ELASTOMERS (115)

Materials	Exposure Dose		Initial Properties			Age	Tensile Strength, A %	Remarks
	ergs g ⁻¹ (C)	roentgen x 10 ⁻⁶	Hardness		Elongation Per Cent			
			shore A	A %				
Vinylpyridines								
Philprene VP-A-1	0	0	70		355		2455	Black
	4.4 x 10 ⁸	5		7.1		-15.0		17.8
	8.7 x 10 ⁸	10		8.6		-24.9		19.1
	4.4 x 10 ⁹	50		17.1		-54.7		26.8
	8.7 x 10 ⁹	100		22.0		-70.3		15.0
	2.6 x 10 ¹⁰	300		35.7		-92.0		-41.3(a)
	4.4 x 10 ¹⁰	500		42.9		-98.6		63.8(a)
Philprene VP-A-2	0	0	81		365		1855	Black
	4.4 x 10 ⁸	5		3.7		-1.6		-0.5
	8.7 x 10 ⁸	10		3.7		-6.0		1.3
	4.4 x 10 ⁹	50		8.6		-49.0		2.2
	8.7 x 10 ⁹	100		14.8		-68.7		11.8
	2.6 x 10 ¹⁰	300		18.5		-86.1		50.3
	4.4 x 10 ¹⁰	500		23.5		-93.6		106.8(a)
Philprene VP-A-3	0	0	85		546		3806	Black
	4.4 x 10 ⁸	5		2.4		-29.1		-27.4
	8.7 x 10 ⁸	10		3.0		-30.0		-27.0
	4.4 x 10 ⁹	50		7.1		-64.0		-20.6
	8.7 x 10 ⁹	100		9.4		-77.9		-30.4
	2.6 x 10 ¹⁰	300		15.9		-90.8		-11.8(a)
	4.4 x 10 ¹⁰	500		17.7		-100.0		12.3(a)
Philprene VP-16-1	0	0	22		400		2700	Black
	4.4 x 10 ⁸	5		5.5		-21.0		7.6
	8.7 x 10 ⁸	10		6.1		-21.0		8.8
	4.4 x 10 ⁹	50		16.2		-69.4		-7.6
	8.7 x 10 ⁹	100		23.5		-81.0		-16.4
	2.6 x 10 ¹⁰	300		33.8		-88.0		-34.4
	4.4 x 10 ¹⁰	500		41.3		-95.1		-37.7(a)
Philprene VP-25-1	0	0	75		422		3125	Black
	4.4 x 10 ⁸	5		4.3		-22.0		-2.4
	8.7 x 10 ⁸	10		5.2		-23.2		-3.6
	4.4 x 10 ⁹	50		14.9		-59.9		-9.3
	8.7 x 10 ⁹	100		20.0		-69.1		-19.0
	2.6 x 10 ¹⁰	300		28.6		-89.0		-27.3
	4.4 x 10 ¹⁰	500		36.7		-92.4		-50.1(a)
Philprene VP-25-2	0	0	27		196		2145	Black
	4.4 x 10 ⁸	5		2.3		0.0		1.9
	8.7 x 10 ⁸	10		3.5		0.0		2.3
	4.4 x 10 ⁹	50		5.6		-35.8		11.8
	8.7 x 10 ⁹	100		8.1		-58.1		24.3
	2.6 x 10 ¹⁰	300		11.5		-83.2		42.2(a)
	4.4 x 10 ¹⁰	500		14.9		-100.0		26.3(a)

(a) Broke when bent 180 degrees.

Work by Sisman and Ropp⁽⁵⁾ has indicated that threshold damage is reached for nitrile rubber containing 35 to 40 per cent acrylonitrile at an absorbed dose of 2×10^8 ergs g^{-1} and 25 per cent damage accrued at 7×10^8 ergs g^{-1} . For this higher-acrylonitrile-type rubber, it was found that the compression set degrades by about 25 per cent at an exposure dose of 7×10^8 ergs g^{-1} (C). Its tensile strength at first increases by about 40 per cent and then decreases, and increases by about 25 per cent at 1.6×10^{10} ergs g^{-1} (C).

Recent work by Born⁽¹¹⁾ indicates that the higher-acrylonitrile-containing polymers were the more stable when exposed up to 3.5×10^9 ergs g^{-1} (C). At 10^{10} ergs g^{-1} (C), crosslinking appears to increase with increased nitrile content.

Harrington⁽¹²⁷⁾ at General Electric determined the radiation stability of three nitrile rubbers containing differing amounts of acrylonitrile. Two series were run, one without carbon black and with a minimum of compounding ingredients and one containing carbon black and the usual compounding materials. The nitrile rubbers used represented very high (50 per cent), medium-high (33 per cent), and low (20 per cent) acrylonitrile contents. Table A-67 gives the recipes used for this series of tests while Figure 13 and Table A-68 show the effect of acrylonitrile content on the gamma-radiation induced changes in the physical properties of nitrile elastomers.

Harrington summarized these effects of acrylonitrile content, stating that for the properties examined (tensile strength, elongation, and hardness), changes induced by radiation appeared to be a function of the acrylonitrile content. These changes are as follows:

- (1) At radiation doses up to 2.6×10^{10} ergs g^{-1} (C), the rate and per cent of increase in tensile strength is greater for those rubbers containing higher amounts of acrylonitrile than for those containing less acrylonitrile, the rate of increase being greater as exposures are increased.
- (2) Elongation follows a different pattern. Nitrile rubbers containing the larger percentages of acrylonitrile have the higher original elongations. When irradiated, elongations of these rubbers decrease, but the rate of decrease is not uniform. At low radiation doses, the per cent decrease is greater for elastomers having higher acrylonitrile contents than for those containing less acrylonitrile, but at higher doses, this is reversed. At an exposure dose of approximately 10^{10} ergs g^{-1} (C), elongation of nitrile rubbers tested approached a common value regardless of the nitrile content. At the highest dose examined [2.6×10^{10} ergs g^{-1} (C)], the samples containing the smaller amounts of acrylonitrile retained their elongation better than those having higher acrylonitrile contents, although in all cases elongation values were low.
- (3) With respect to hardness, acrylonitrile content apparently has no significant effect on the increase caused by exposure to ionizing radiation.

Data on carbon black-filled nitrile rubbers show that the amount of acrylonitrile has the same influence on the radiation stability of the filled as on that of the unfilled materials. However, the filler and curing system may reduce the effect. Parker and co-workers⁽¹³⁶⁾ studied the effects of gamma irradiation on a group of four

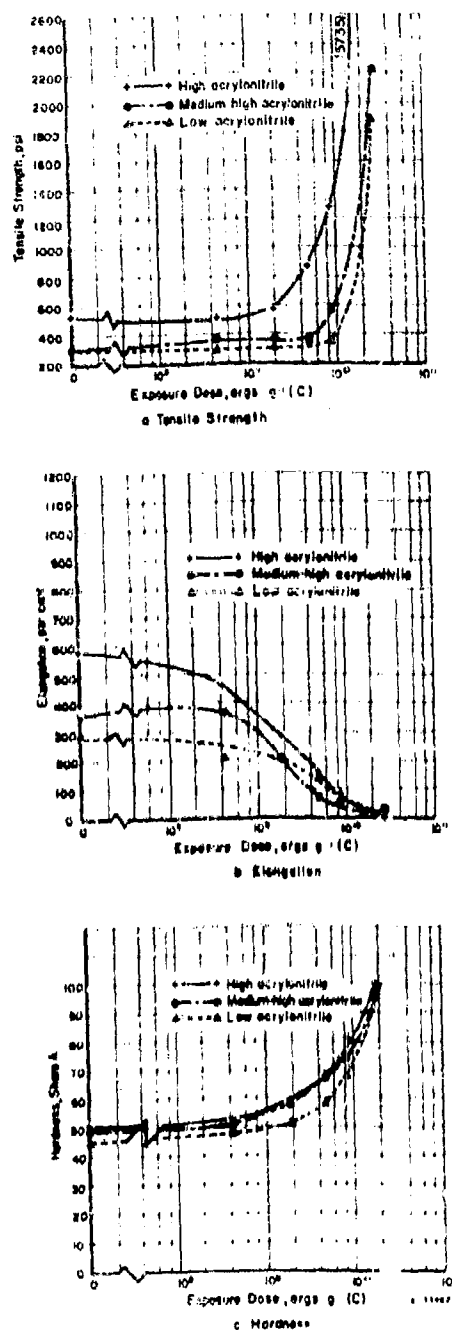


FIGURE 13. EFFECT OF RADIATION ON THE MECHANICAL PROPERTIES OF NITRILE ELASTOMERS CONTAINING VARIOUS AMOUNTS OF ACRYLONITRILE (127)

acrylonitrile-butadiene copolymers containing 50, 40, 33, and 20 per cent acrylonitrile, respectively. They found, as did Harrington, that the nitrile rubbers increased in tensile strength when irradiated; the greater the percentage of acrylonitrile, the greater the increase in tensile strength. In addition, Parker studied the effect of various types of cures on the radiation stability of these copolymers. Sulfur, peroxide, and radiation cures were investigated.

With peroxide-cured materials, the 50 per cent acrylonitrile copolymer was the most stable while the rubber containing 33 per cent acrylonitrile was the least stable. The peroxide-cured 50 per cent acrylonitrile rubber was the most stable of the nitrile rubbers tested. With the radiation-cured material, the 40 per cent acrylonitrile compound had the greatest stability and again the 33 per cent acrylonitrile copolymer was the least stable. The sulfur-cured materials were more stable than the peroxide- and radiation-cured materials at acrylonitrile concentrations of less than 33 per cent, but less stable to radiation at the higher acrylonitrile concentrations. They found the 20 per cent acrylonitrile rubber to be the most stable of the sulfur-cured rubbers. On the other hand, Born⁽¹¹⁾ reported that a 70:30 butadiene-acrylonitrile copolymer was the most stable of a series of 90:10, 80:20, 70:30, and 50:50 sulfur-cured copolymers.

Harrington studied the effect of filler on acrylonitrile rubber. (27) He reported that, with a 33 per cent acrylonitrile copolymer, as the carbon black loading was increased up to about 40 parts per hundred resin, tensile strength was lowered for low radiation exposures. At intermediate and high doses, tensile strength increased. However, Harrington pointed out that nitrile rubber with no filler has a low tensile strength, while 40 to 80 parts carbon black increases the tensile strength of the rubber by a factor of 10 (300 psi to about 3,100 psi). These original tensile values must be considered along with the effect of the changes due to irradiation.

A filler loading of 5 to 40 per cent carbon black increases the ultimate elongation of nitrile rubber, the maximum elongation being reached with about 15 parts per hundred carbon black. With irradiation, increasing amounts of carbon black result in a greater decrease in elongation.

Harrington found that hardness changes were relatively unaffected by the amount of carbon filler, but that the less the carbon black, the greater the flexibility of the rubber at any given exposure. Harrington's data are included in Table A-69 and A-70, and Figure 14. (127)

The effect of filler on nitrile rubber was also studied at Convair⁽¹⁷⁾. Formulations based on Hycar 1001, a high-acrylonitrile NBR, and on Hycar 1052, a medium-high-acrylonitrile NBR which was polymerized at low temperature, and two commercial formulations, were irradiated in air, nitrogen JP-4 fuel, and in Oronite 8515 oil. Samples irradiated in the JP-4 fuel were immersed 1 week before irradiation and for 30 days after irradiation. They were then removed from the fuel and tested within 2 hours. Samples irradiated in the oil were immersed 1 week before irradiation and removed 30 days after irradiation. The formulations are given in Table A-71 and test results in Table A-72. It was found that, although a filler is necessary for high tensile strength with nitrile rubber, the percentage of carbon black did not influence to any appreciable extent the radiation stability in air. The tensile strength of materials compounded with Hycar 1001 generally increased with radiation dose while tensile strength of materials compounded with Hycar 1052 generally decreased. However, the filler apparently had a finite effect on the tensile strength of the elastomers while immersed in JP-4 fuel.

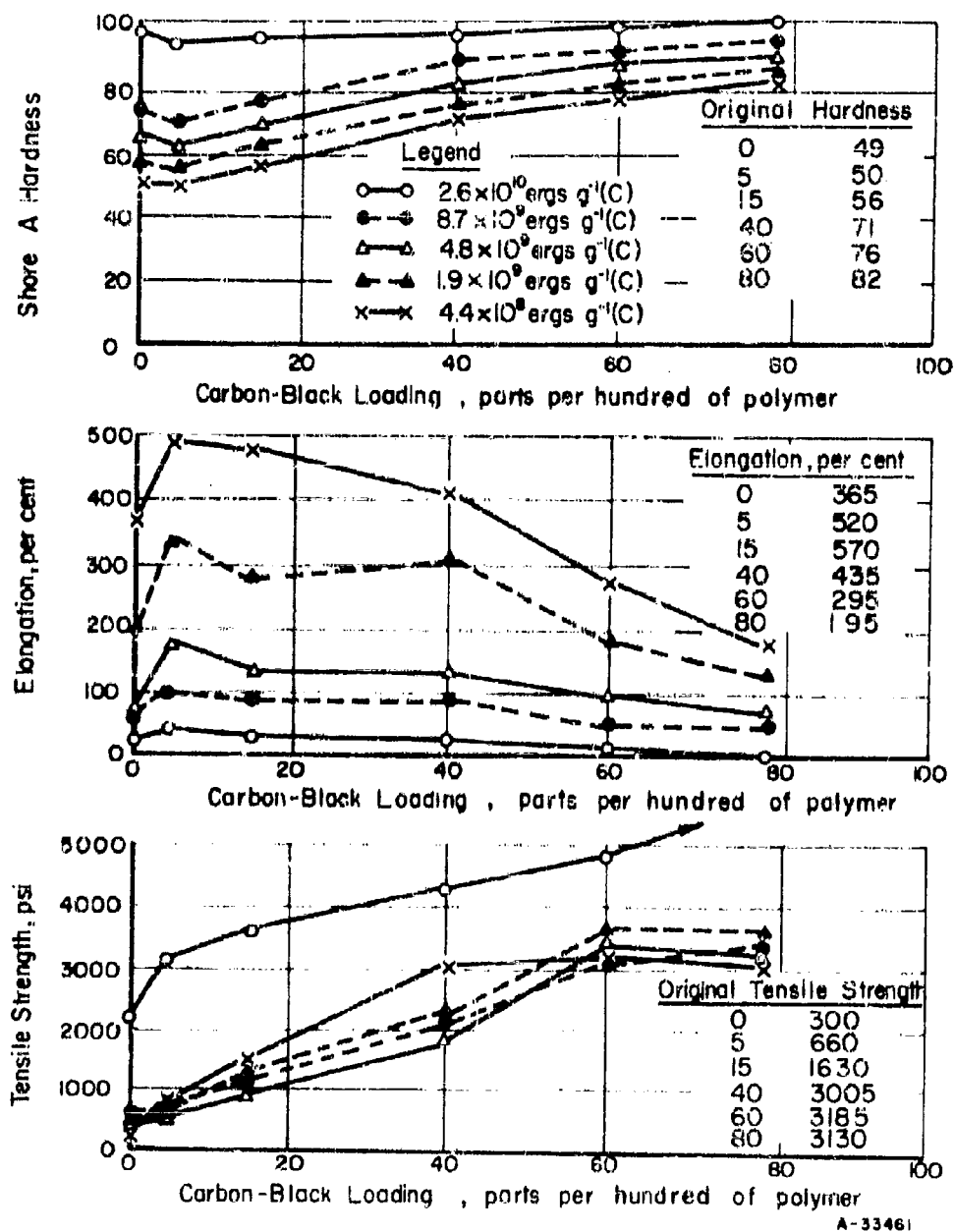


FIGURE 14. EFFECT OF CARBON-BLACK LOADING ON THE GAMMA-RADIATION-INDUCED CHANGES IN THE PHYSICAL PROPERTIES OF A 67:30 BUTADIENE-ACRYLONITRILE ELASTOMER^(1,28)

The tensile strength of carbon black-filled elastomers decreased markedly when irradiated in the fuel. Those without carbon black, although having a low initial tensile strength, were more resistant to radiation. There was no difference in the effects on elongation.

Johnson and Sicilio at Convair, comparing nitrile rubbers having a hardness of 40 and 60 to 70, found little difference between the effects of radiation at a dose of 2.4×10^9 ergs g^{-1} (C) on the two materials.⁽¹¹⁵⁾ Original tensile strengths of the two materials were the same, and after irradiation the differences were slight. Both rubbers showed very good stability to this radiation exposure (see Table A-73).

Nitrile-rubber packing compounds, fuel-cell liners, and hose tube stocks were irradiated and tested at room temperature and 158 F by workers^(11, 51) at The B. F. Goodrich Co. Tables A-74, A-75, and A-76 show the data for these tests. The hose stock contained 85 parts of nitrile rubber and 13.67 parts of SBR rubber by weight. Also included are data for a nitrile rubber-vinylite bladder stock for comparison purposes. These data are found in Table A-77.

An examination of these tables will show that nitrile rubber stocks are affected to a much greater degree by heat than by radiation. Tensile strength was not affected by 158 F irradiation to any appreciably greater extent than room-temperature irradiation except for the nitrile rubber-SBR tube stock (Table A-76). Tensile strength of this rubber increased when irradiated at room temperature. When irradiated at 158 F, the tensile strength increased until an exposure dose of 1.7×10^9 ergs g^{-1} (C) was reached and then decreased to approximately the original value at a dose of 5.9×10^9 ergs g^{-1} (C), the maximum exposure dose for this test. Heat and radiation effects were found not to be additive. Changes in elongation and hardness were about equivalent for both room-temperature and 158 F irradiation. Antirads, quinhydrone, or Akroflex C, gave only a slight improvement at room temperature and 158 F and that was primarily with respect to elongation. Generally, nitrile rubber stocks containing quinhydrone showed greater improvement in stability than did those containing Akroflex C.

Compression set of these nitrile rubber stocks was also determined in air and immersed in an alkyl diphenyl ether hydraulic fluid.⁽⁵¹⁾ The samples were compressed 25 per cent and irradiated while under compression. Table A-78 gives the dose required for 50 per cent set and the compression set after an exposure of 5.23×10^9 ergs g^{-1} (C).

Examination of the results of nitrile-rubber stocks irradiated at room temperature while under 25 per cent compression shows that there is little difference between the compression set induced by radiation whether the samples are in air or in the hydraulic fluid. The compression set of nitrile rubber is greatly increased when the rubber is irradiated while compressed. Antirads provide some improvement in radiation-induced compression set of this rubber. The maximum improvement in compression set is seen in the nitrile-rubber bladder stock containing quinhydrone when irradiated while immersed in alkyl diphenyl ether. Compression set was lowered 20 per cent at an exposure dose of 5.23×10^9 ergs g^{-1} (C). Compression set results obtained at Convair⁽¹⁷⁾ were in agreement with the Goodrich results. See Table A-79 in the Appendix for Convair test results.

The addition of five parts of an antioxidant (Antiox 4010) improves radiation resistance.⁽¹³³⁾ One composition did not become stiff or brittle until an exposure dose of 5×10^{10} ergs g^{-1} (C) had been reached. The addition of a phenolic resin to a nitrile elastomer composition appears to improve radiation resistance slightly.

All nitrile-type elastomers except the carboxylic type, such as Hycar 1072, tend to stress crack. Hycar 1072 did not stress crack at 2.6×10^{10} ergs g^{-1} (C). It is interesting to note also that this polymer is resistant to ozone cracking. The various data therefore suggest that oxidation is the major factor in radiation deterioration of nitriles. Studies indicate oxidation is very pronounced after exposure to approximately 4.3×10^9 ergs g^{-1} (C). Therefore, in preparation of nitrile rubber compositions for radiation use, antirad and antioxidants should be utilized. Some nitrile rubbers were tested in component systems. These were discussed in the section on components.

More recently, DeZel⁽³⁰⁾ irradiated butadiene acrylonitrile rubbers at gamma doses ranging from 9.3×10^6 to 1.86×10^{11} ergs g^{-1} (C). Recipes for the compounds used in this study are listed in Table 40; the results of exposures to various radiation doses are presented in Table 41. Compound PXU 3005A (nitrile type) was relatively unaffected by radiation up to 9.3×10^{10} ergs g^{-1} (C). An increase in the 100 per cent modulus possibly indicated a beginning of a deterioration trend. The volume change of 3005A after 72 hours immersion in Type III fuel was slight except at 9.3×10^9 ergs g^{-1} (C) which had an approximate twofold increase; a large change occurred at 9.3×10^9 ergs g^{-1} (C). No significant changes were noted with Compound PXU 5333 (butadiene blend). O-rings prepared from PXU 5333 (and MIL-P-5516) and tested in a jig at varying pressures and temperatures passed all tests up to 200 psi in JP-4 fuel at room temperature; however, failure occurred at -65 F. Failure also occurred when using MIL-O-5606 at 3000 psi and -30 F.

TABLE 40. RECIPES FOR ELASTOMERIC COMPOUNDS

Ingredient	PXU 3005A	PXU 5333
Hycar 1001 ^(a)	100.0	--
Hycar 1002 ^(b)	--	80.0
Philprene VP-15 ^(c)	--	20.0
Neozene D	1.0	--
Zinc oxide	5.0	5.0
Lotharge	2.5	--
Stearic acid	--	1.1
SPF carbon black	40.0	--
ISAF carbon black	--	25.0
Tetramethyl thiuram disulfide	2.5	1.1
Zinc dibutyl dithiocarbamate	2.5	--
Benzo thiazyl disulfide	--	0.8
2-Mercapto benzothiazole	--	0.1
Tellurium diethyl dithiocarbamate	--	1.6
Telloy	--	0.6
Tetra chlorobenzoquinone	--	2.0
Cure	45 min/310 F	60 min/310 F

(a) Butadiene-acrylonitrile copolymer; ~40 per cent combined acrylonitrile.

(b) Butadiene-acrylonitrile copolymer; ~33 per cent combined acrylonitrile.

(c) Vinyl pyridine rubber.

TABLE 41. EFFECTS OF RADIATION ON NITRILE ELASTOMERS

Compound	Exposure, erg: g ⁻¹ (C)	Tensile Strength, psi	Elongation, per cent	100 Per Cent Modulus, psi	Fuel Swell, per cent volume change	Brittle Point, F
PXU 3005 A	Control	2782	575	--	25.0	-27
	9.3×10^6	2720	910	227	24.6	-20
	9.3×10^7	2450	830	241	28.5	-20
	9.3×10^8	2800	860	220	27.9	-10
	9.3×10^9	2850	850	267	46.1	-35
	9.3×10^{10}	2315	820	301	25.2	-10
PXU 5333	Control	3000	450	--	45.0	-90
	9.3×10^6	3090	430	610	39.1	-104
	9.3×10^7	3075	430	535	50.0	-104
	9.3×10^8	2760	380	541	52.0	-162
	9.3×10^9	3170	430	634	51.0	-107
	9.3×10^{10}	2940	380	566	49.3	-107

Neoprene Rubber

Neoprene rubbers (polychloroprenes) are resistant to aliphatic oils and have excellent resistance to outdoor weathering, ozone, and heat (up to 250 F). They have good processing characteristics, and the physical properties of the pure gum compounds are good. They have poor resistance to aromatic oils; chlorinated and other polar solvents have a swelling action on neoprene. Neoprene is similar to nitrile rubber with respect to radiation resistance. Data suggest that chain cleavage occurs with neoprene at lower exposure dosages. At higher exposure dosages, where there is an abrupt rise in tensile strength, crosslinking predominates. Neoprenes do not show evidence of stress cracking at 1×10^{10} ergs g⁻¹ (C).

Harrington⁽¹³⁷⁾ summarized his work on how radiation affects the physical properties of six commonly used types of neoprene polymers, and how some compounding ingredients contribute to these changes. In general, tensile strength is the property most sensitive in reflecting the changes caused by different amounts and types of compounding ingredients. Fillers, in particular, regulate the behavior of tensile strength. Flexibility is also a relatively sensitive property for reflecting changes in neoprenes after irradiation. Oxygen apparently plays a minor role in radiation-induced damage to neoprene. An analysis of the data showed that frequently certain effects caused by materials are masked out by effects of others. Over-all changes are roughly a sum of individual net effects.

Tensile strength of irradiated neoprene varies depending on the type of polymer, cure, and additives, but in general, tensile strength decreases up to a radiation exposure dose of 4.3 to 8.7×10^9 ergs g⁻¹ (C)⁽¹²¹⁾ and then increases with increasing radiation. Elongation decreases with increased radiation dose, while hardness does not change up to an absorbed dose of 4.5×10^9 ergs g⁻¹ (C).⁽¹²¹⁾

Aromatic plasticizers appear to make neoprene compositions more stable under radiation. A composition containing 50 parts of such a plasticizer showed little change in mechanical properties on exposures to 8.7×10^9 ergs g⁻¹ (C).

Johnson and Sicilio⁽¹¹⁵⁾ at Convair irradiated a neoprene rubber compounded to have a Shore A durometer hardness of 40 and one compounded for a hardness of 70 to 80. The rubber was not identified as to type. These compounds were irradiated to an exposure dose of 2.4×10^9 ergs g^{-1} (C) (6×10^{14} fast n cm^{-2} , 6×10^{13} nvt, and 5×10^{16} γ cm^{-2}). No changes in mechanical properties were noted except for a slight decrease in tear strength. Data are given in Table A-80.

Three neoprene aircraft compounds were included in the test that workers at The B. F. Goodrich Co. conducted on the combined effects of radiation and elevated temperatures on rubber compounds. (11, 51) A neoprene wire insulation, hose tube stock, and packing compound were irradiated and tested at room temperature and at 158 F. The insulation and tube stocks were based on Neoprene GN while the packing compound was based on a 60:40 Neoprene W-Neoprene WHV formulation. The results of these tests are shown in Tables A-40, A-56, and A-81. The packing compound had very poor radiation stability. This, combined with poor retention of properties at 158 F, gave a material with very low tensile strength and per cent elongation when irradiated at 158 F. The other two compounds showed better radiation stability although their initial tensile strengths were lower than that of the packing compound. When irradiated at 158 F, but tested at room temperature, the combined effects of heat and irradiation of the packing compound appeared to be greater than the additive effect for heat and radiation. However, when tests were run at 158 F, the combined effects were less than the addition of the radiation and heat effects.

These compounds were also irradiated while compressed 25 per cent and the compression set determined. Table 42* gives the compression set when irradiated in air and when irradiated while immersed in an alkyl diphenyl ether (C₁₄-C₁₆) hydraulic fluid.

Neoprene is reported to swell badly in the alkyl diphenyl ether hydraulic fluid.

Hypalon (Chlorosulfonated Polyethylene)

Hypalon has extremely good resistance to oxidation and has good mechanical properties. Although its resilience is generally lower than that of most rubbers at room temperature, it is equal to or better than those of other elastomers at 212 F. It can be used continuously at temperatures up to 250 F and for intermittent service to 350 F, and can be compounded for low-temperature resistance, having a brittle temperature of -40 to -80 F. It has good resistance to oil, greases, and chemicals. It is resistant to fuming nitric acid, but it is adversely affected by continuous contact with aromatic or chlorinated hydrocarbons.

Born⁽¹³²⁾ describes the radiation resistance of the pure gum compound of Hypalon as good, but the radiation stability of the black stock is described as being between those of nitrile and polyacrylic rubbers. Tests are limited, but Bopp and Sisman⁽⁷⁶⁾, and Born⁽¹³²⁾ indicate that the radiation stability of Hypalon is slightly less than the average radiation stability of the elastomers.

On irradiation the tensile strength of Hypalon⁽¹³³⁾ follows two trends: (1) it remains fairly constant at approximately the original tensile-strength value up to 8.7×10^9 ergs g^{-1} (C), after which it continues to increase with higher exposure dose, and (2) it increases at low exposure doses, drops considerably at about 4.3×10^9 ergs g^{-1} (C), and then continues to increase on continued exposure. Hardness increases and elongation decreases with continued exposure.

* Table F is duplicate of Table 18. It is repeated here for the reader's convenience in making comparison with the text.

TABLE 42. COMPRESSION SET OF NEOPRENE AIRCRAFT COMPOUNDS IRRADIATED IN AIR AND IN ALKYL DIPHENYL ETHER (C₁₄-C₁₆) HYDRAULIC FLUID(51)

Compound	Antirad	Environ- ment	Preirradiation Compression Set		Compression Set After Exposure at 5.23×10^5 Ergs G ⁻¹ (C)	Dose Required for 50 Per Cent Compression Set, 10^5 ergs. g ⁻¹ (C)
			Average Time, days	Average Set, per cent		
Wire Insulation	None	Air	46	49.3	81.7	1.65
	Akroflex C	Air	45	45.0	78.5	1.31
	Quinhydrone	Air	46	49.4	79.2	1.57
	None	Hydraulic	70	37.4	80.3	1.07
	Akroflex C	fluid	64	40.1	83.8	1.58
	Quinhydrone		67	37.0	70.7(a)	
Packing compound	None	Air	40	20.4	75.0	1.31
	Akroflex C		47	16.2	76.8	2.18
	Quinhydrone		40	42.0	82.3	0.70
	None	Hydraulic	70	8.7	82.3	1.22
	Akroflex C	fluid	71	7.1	70.7	1.80
	Quinhydrone		72	23.0	70.3	1.26
Hose tube stock	None	Air	48	30.5	74.1	1.48
	Akroflex C		48	42.7	70.1	1.00
	Quinhydrone		48	32.7	70.1	1.00
	None	Hydraulic	70	25.1	77.3	1.00
	Akroflex C	fluid	67	30.7	75.2	1.32
	Quinhydrone		69	20.4	79.3	1.07

(a) Compression set after exposure at 4.36×10^5 ergs g⁻¹ (C).

Data suggest that aromatic plasticizers such as Kenflex A improve stability. Antirads alone do not seem to have any appreciable effect on stability. There is no evidence of flex cracking of Hypalon-type compositions on radiation exposure. Hypalons appear to undergo crosslinking at low and higher radiation doses with few exceptions.

Recent information indicates that the compression set of Hypalon is higher than that for most elastomers and therefore its use as a gasket material may be limited. (138)

Harrington⁽¹²⁷⁾ determined the effect of gamma radiation on the mechanical properties of both litharge-magnesia-cured and epoxy-cured Hypalon compounds. The epoxy-cured material increased in tensile strength to an exposure dose of 1.9×10^9 ergs g^{-1} (C), but decreased with higher exposure, losing 22 per cent of its original tensile strength (original tensile strength was 1980 psi) at a dose of 8.7×10^9 ergs g^{-1} (C). The litharge-magnesia-cured material decreased at intermediate doses, but at high doses tensile strength increased rapidly. Elongation of both materials decreased with increasing radiation exposures. Data are given in Tables 43 and 44.

TABLE 43. EFFECT OF GAMMA RADIATION ON THE MECHANICAL PROPERTIES OF CHLOROSULFONATED POLYETHYLENE RUBBERS⁽¹²⁷⁾

Hanford Sample Designation	Material	Exposure Dose		Initial Properties and Per Cent Change						Remarks
		ergs g ⁻¹ (C) x 10 ⁻⁹	roentgen x 10 ⁻⁶	Hardness		Elongation		Tensile Strength		
				Shore A	A %	Per Cent	A %	PSI	A %	
A2109D-8	Hypalon 20 (litharge- magnesia cured)	0	0	60		410		1810		Black
		0.44	5		0.0		-22.0		-2.9	
		1.0	22		20.0		-48.0		11.6	
		4.8	56		23.3		-73.2		-29.0	
		8.7	100		30.7		-85.4		-37.8	
		20	300		65.0		-97.0		61.3	(a)
A2109D-9	Hypalon 20 (epoxy cured)	0	0	55		350		1980		Black
		0.44	5		7.3		-25.7		0.6	
		1.0	22		20.0		-48.8		11.8	
		4.8	56		32.7		-62.9		7.3	
		8.7	100		38.2		-71.4		-22.4	
		20	300		56.4		-91.4		-44.9	(a)

(a) Broke when bent 180 degrees.

TABLE 44. RECIPES FOR CHLOROSULFONATED POLYETHYLENE RUBBERS TESTED FOR RADIATION STABILITY⁽¹²⁷⁾

Material, parts by weight	Hypalon A2109D-8	Hypalon A2109D-9
Hypalon 20	100.0	100.00
Litharge	20.0	--
Magnesia	10.0	--
SRF Black	10.0	20.00
N3C	3.0	--
MBTS	0.5	0.50
Tetron A	0.5	1.50
Epon 828	--	15.00
DOTG	--	0.25
Cure, min/°F	30/307	30/307

Polyacrylic Rubber

Polyacrylic rubbers (saturated polyesters of acrylic acid) are very resistant to oxygen, ozone, and light. They are heat resistant to 350 F and resistant to swelling and deterioration in oils, particularly sulfur-bearing oils at elevated temperatures. The radiation stability of acrylic rubbers is slightly inferior to those of nitrile and neoprene rubbers. A dose of 10^9 ergs g^{-1} (C) will effect an over-all change in physical properties of 25 per cent.

Butyl and ethyl acrylate materials appear to behave similarly on radiation. Their hardness increases with increasing exposures. In general, tensile strength increases or decreases after short exposure, remains relatively unchanged for intermediate exposures, and drops, then eventually increases with prolonged exposure.

Data suggest that, in general, acrylics undergo, up to 8.7×10^9 ergs g^{-1} (C), slight amounts of both crosslinking and chain cleavage with cleavage predominating. At high exposure doses, crosslinking predominates. After an exposure dose of 4.3×10^{10} ergs g^{-1} (C), their tensile strength decreases, which is indicative of the predominance of chain cleavage. There is no evidence of stress cracking of acrylate-type polymers.

The polymer-type materials may be a factor as to radiation resistance; for example, for the copolymer of ethyl acrylate and chlorovinyl ether (Hycar 4021), the tensile strength is lowered considerably at short and intermediate exposure doses before it rises at the higher exposure doses. (133)

Polyacrylic rubber, like most elastomers, develops a high compression set when irradiated while compressed. Data reported for Hycar PA-21(51) are presented in Table 45.

TABLE 45. RADIATION-INDUCED COMPRESSION SET OF POLYACRYLIC RUBBER⁽⁵¹⁾

Antirad	Preirradiation Compression Set		Compression Set After Exposure at 5.23×10^9 Ergs G^{-1} (C), per cent	Dose Required for 50 Per Cent Compression Set, ergs g^{-1} (C)
	Average Time, days	Average Set, per cent		
None	32.5	13.7	87.9	8.4×10^8
UOP-88	32.5	12.8	62.6	3.74×10^9

Hycar PA-21 showed the most response to potential antirads with respect to compression set of any of the rubbers tested. (51)

Silicone Rubbers

Silicone rubbers are highly resistant to high and low temperatures. They can be used over a temperature range of -100 to >500 F. Tensile properties of most silicone rubbers are relatively poor. To obtain good tensile strength and maintain

high-temperature properties, silicone rubbers are usually reinforced with inorganic fillers, such as silica. Oil, fuel, and fluid resistances of these rubbers are generally inferior to those of nitrile or neoprene rubbers. However, some modified silicones, such as the methyltrifluoropropyl and nitriloalkyl siloxanes, have good oil resistance.

A variety of silicone elastomers, having different chemical constituents, are manufactured today. These consist of six types: dimethyl, methylphenyl, methylvinyl, methylphenylvinyl, methyltrifluoropropyl, and nitriloalkyl siloxanes. Compositions of most of these have been irradiated and their physical and mechanical properties determined after irradiation.

On irradiation, the damage to silicones will vary with the type and amount of irradiation, the composition of material, time of cure, the volume of the sample exposed, and environmental factors. Radiation attacks silicones directly and indirectly by ionizing the molecules, which indirectly leads to the formation of free radicals, ethylenic unsaturation, and molecular rearrangement. As a result, both crosslinking and chain scission occur simultaneously, but not to the same extent.

The principal effects of irradiation of silicone rubbers are those of crosslinking. According to Born, the resultant effect is equivalent to overvulcanization⁽¹³⁹⁾. The hardness, stiffness, resilience, hysteresis, and modulus of the rubber compound increase during irradiation. The abrasion resistance, tensile strength, and ultimate elongation decrease. A few exceptions exist in which chain scission predominated. The tensile strength, ultimate elongation, modulus, and hardness of these rubber compounds decrease.

It has been noted that radiation damage to silicone rubber is less severe in an inert atmosphere than in air. Immersion of the rubber in lubricants, fuels, and hydraulic fluids during irradiation may inhibit deterioration, especially if air is excluded from the system. Certain types of stresses increase the radiation damage; for example, stretching, twisting, shearing, and swelling forces. On the other hand, compression may decrease radiation damage.

In general, silicone elastomers on irradiation increase in hardness and tensile strength and decrease in elongation. Compression set after irradiation is usually poor, being in the range of 88 to 100.

It is felt at Convair that compression-set data obtained after irradiation gives misleading information.⁽¹⁴⁰⁾ The purpose of compression set is to test the cure of a rubber. Undercured specimens have high compression set while that of overcured samples is low. However, if the sample is placed under compression during irradiation, the amount of curing shows up as a sharp increase rather than a decrease in compression set. Crosslinking occurs in the stressed position making the per cent set very sensitive to irradiation. In tests performed at Convair, Newell reports a permanent set due to irradiation of 100 per cent for Silastic 7-170 (dimethyl siloxane) and Silastic 250 (methylphenyl siloxane).

In general, it appears from Harrington's work⁽¹⁰⁰⁾ that the radiation resistance of the silicone elastomer depends on the type and amount of organic groups on the main silicone chain. The phenyl types are more resistant because of the presence of the aromatic ring, which very likely absorbs the radiation energy without affecting the other

parts of the molecule. The dimethyl silicones increase both in hardness and tensile strength on irradiation. There is a decrease in elongation. This type of silicone will break when subjected to bend test after exposure doses of 4.3×10^9 to 5.2×10^9 ergs g^{-1} (C). Silastic 160 broke after an exposure dose of 8.7×10^9 ergs g^{-1} (C). Methyl vinyl silicones increase in hardness with increase in radiation. These materials break on bending after exposure doses of 4.3×10^9 to 8.7×10^9 ergs g^{-1} (C). Certain methyl phenyl silicones, such as GE 81504 and Silastic 675, retain flexibility up to 2.6×10^{10} ergs g^{-1} (C). Most of these materials decrease in tensile strength with increase in radiation, and all harden on radiation exposure. Methyl phenyl vinyl silicones act similarly to methyl phenyl silicones, and those tested broke on bending after 8.7×10^9 ergs g^{-1} (C).

In evaluating radiation-effects data on silicone rubbers it has been found that investigators do not always agree as to the resistance to radiation shown by the different types of silicone elastomers. Warrick, of Dow Corning Corporation, reports that a phenyl-type siloxane rubber with about 80 per cent of phenyl can absorb more than five times as much radiation as conventional dimethyl siloxanes for equal damage⁽¹⁴²⁾. He states that this type of silicone rubber "is comparable to the best combination of antirad and natural rubber in room-temperature radiation exposure and is outstanding in a combined radiation and temperature environment (200 C)". Harrington⁽¹⁰⁰⁾, of General Electric Company, explains that phenyl types are superior due to the presence of the benzene ring which can absorb more energy without disruption of the molecular structure. In his opinion, the methylvinyl types are intermediate and dimethyl compounds rank third. In all cases, experimenters have found that fluorinated silicones are least resistant to radiation.

On the other hand, at Convair, Fort Worth, Texas, Newell finds no evidence that any of the three principal groups, dimethyl, methylphenyl, and methylvinyl, is more resistant to radiation than the other two⁽¹⁴³⁾. He reports that methylvinyl siloxane and dimethyl siloxane show the best radiation resistance.

Data from tests performed by Harrington and that of Newell are presented in Figures B-26, B-27, and B-28. It can be noticed that their results differ for certain types. The most significant disagreement exists in values reported for tensile strength. The average value for per cent change in tensile strength of all dimethyl siloxanes tested by Harrington shows an increase of 40.5 per cent while the average value of data reported by Newell is -5 per cent. The average value for tensile strength of dimethyl siloxanes shows an increase from 772 to 1,049 psi as reported by Harrington and a decrease from 816 to 775 as reported by Newell. Methylphenyl siloxane elastomers show a decrease from 834 to 751 psi according to Harrington and an increase from 744 to 818 psi according to Newell. An increase of 127 psi was reported by Harrington for methylvinyl siloxanes while Newell reported a decrease of 226 psi. Newell reported an increase in hardness from an initial value of 75 to 132 for methylphenyl siloxanes. Harrington's data showed an increase of only 60 to 83. The results were relatively consistent for the remainder of the tests. Hardness increased in all cases. Elongation decreases by more than 50 per cent.

The differences in properties on irradiation as found by different investigators may result from differences in the type and state of vulcanization of the resin samples and in the test procedure followed. In the test procedure, the radiation source, dose rate, and approximations made in calculation of dose rate are important variables. Consequently, in reporting data it is extremely important to indicate (1) a full history of the specimen

tested, as to cure, size of sample and exact composition and (2) exact conditions of test; i. e., source of radiation, dose rate, and the environment of radiation.

Data indicate that there are a number of factors which can influence the reactions taking place on radiation of silicone elastomers. These are (1) the structure of the silicone molecules, (2) the vulcanization system, and (3) the presence of additives, such as fillers and antirads.

It was mentioned earlier that the reduction in aliphatic constituents of the silicone molecules results in improved radiation-resistant elastomers. This effect has been studied by Warrick⁽¹⁴²⁾ and by Fischer, Chaffee, and Flegel⁽¹⁴⁴⁾ of Dow Corning with both gamma and beta radiation. Figures B-21 and B-22 show the results of these studies. In these figures, the aliphatic groups are represented by $\epsilon_{\text{aliphatic}}$, where

$$\epsilon_{\text{aliphatic}} = \frac{\sum \text{all electrons in aliphatic groups}}{\sum \text{all electrons}}$$

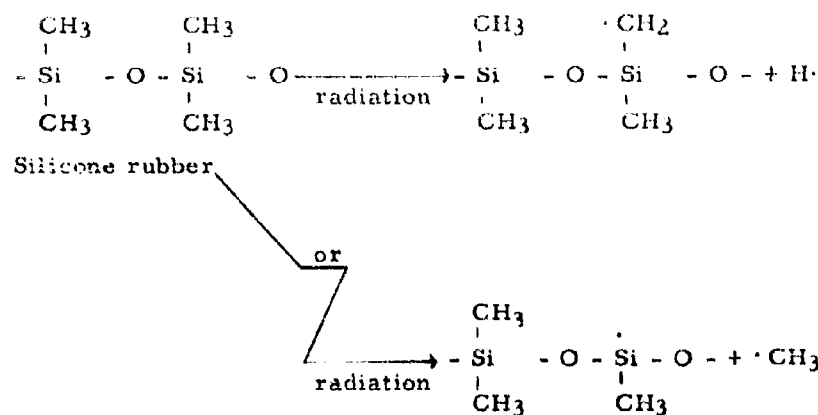
From the figures it can be seen that, with compositions having a low aliphatic content, i. e., 0.126, a marked improvement in radiation is observed. Recent studies indicate that the best radiation-resistant polymer prepared is 23 times more radiation resistant than the standard polydimethyl siloxanes represented by the extreme right of the curves.

Warrick has compared elongation studies performed on low aliphatic silicone elastomers with those performed on other elastomers at room temperature. The comparison (see Table A-82) shows that the low-aliphatic silicones are more resistant to changes in elongation than are organic rubbers, including natural rubber containing an antirad.

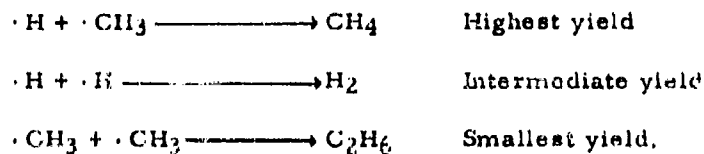
Also, it was found that the same basic relationship held on irradiation with a Van de Graaff generator (beta ray). See Figure B-30.

Further evidence that a reduction in aliphatic in the silicone molecule produces a more radiation-resistant polymer is noted in the work of Prober⁽¹⁵²⁾. He demonstrated the crosslinking or curing of phenylmethyl silicones by radiation. The G-yield for crosslinking of the dimethyl silicones, known to be 4.5, is reduced to about 0.8 in the phenylmethyl silicone system. This may be considered proof that phenyl groups in an organic molecule increase its ability to dissipate high-energy radiation without bond rupture. Cleavage of the silicone-methyl bond occurs more readily than cleavage of the silicon-phenyl bond. Also, during irradiation, silicon-hydrogen bonds are produced. Two-thirds of the Si-H bonds are formed along the chain, the remainder at the terminal silicon atoms. The radiation chemistry in the curing of phenylmethyl silicones compares with that of the curing of dimethyl silicones. The bonds involved in crosslinking are Si-Si and probably SiCH₂Si. Very few crosslinks are formed through the phenyl group.

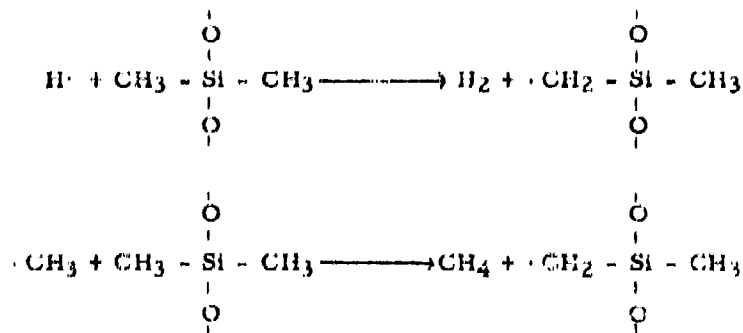
Vulcanization of silicone rubber is postulated, by Epstein and Marans, to occur by a free-radical process⁽¹⁴⁵⁾. During irradiation, methyl groups are subject to attack by fragments of peroxide vulcanizing agents or by free radicals produced by radiation energy. Both hydrogen atoms and methyl radicals are formed and react with each other to give hydrogen, methane, and ethane. They indicate the following as the mechanism for action of radiation on unvulcanized silicones.



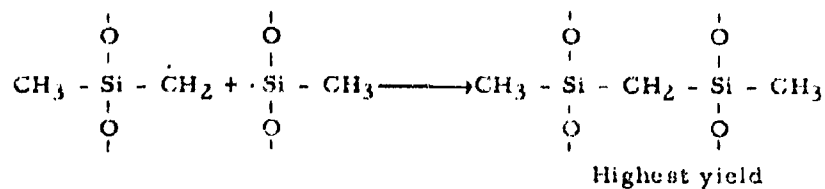
Formation of Gaseous Products

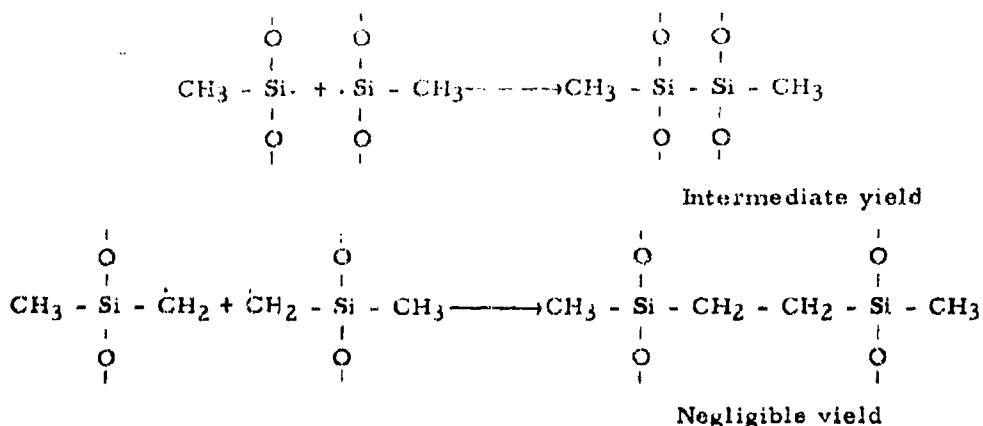


On the other hand, methyl radicals or hydrogen atoms could abstract hydrogen atoms from the chain, resulting in the formation of hydrogen and methane.



Crosslinking occurs in the following manner:





It is the feeling of Warrick and others that extensive crosslinking can be reduced by the addition of phenyl groups. The postulate is that a high level of phenyl linking to silicon acts to absorb radiation through the resonant structure of the benzene ring.

In order to check on the crosslinking phenomenon, Warrick⁽¹⁴⁶⁾ noted the effects of radiation from four different sources: the cyclotron at the University of Pittsburgh, cobalt-60 at Stanford Research Institute, the Van de Graaff generator at High Voltage Engineering Corporation, Boston, and an X-ray generator at Mellon Institute. Attempts were made to use the same equivalence of energy, regardless of source. However this was not possible in all cases. Two points were demonstrated: (1) the effects of secondary radiation on a number of silicone rubbers showed the phenomenon to be similar to aging at high temperature and (2) the nature of the process was shown to be one of crosslinking equivalent to a normal vulcanization.

In studies of vulcanization (crosslinking) by means of gamma rays, samples were tested for strength properties and for crosslinking. The tensile strength, elongation, compression set, and hardness of three samples are summarized in Table 46. The optimum cure appeared to be somewhere above 4.2×10^8 ergs g⁻¹(C) (5 Mrep). Compression set, in this case the percentage of unrecovered compression upon release from clamps after 24 hours' exposure at 150 C, was particularly good at 2.1×10^9 ergs g⁻¹(C) (25 Mrep), although the sample was too highly crosslinked for most purposes.

The amount of crosslinking which occurred in these samples is shown in Table 47. The level of linking was calculated as follows:

$$\text{Moles of links per cc} = \frac{p}{2 Mc}$$

where p = density of filler polymer system and Mc = molecular weight between crosslinks. Warrick's work shows that other forms of radiation yield substantially the same crosslinking effect at about the same dose levels.

Crosslinking of these materials by peroxide curing agents requires high temperatures and long curing times and may leave undesirable residual products. It has been found, however, that the dimethyl silicones may be cured rapidly at low temperatures by high-energy radiation without the introduction of any foreign materials.

TABLE 46. EFFECT OF GAMMA RADIATION FROM COBALT-60
ON THE MECHANICAL PROPERTIES OF SILICONE
RUBBER (142)

Hours	Mrep	Dose ergs g ⁻¹ (C)	Hardness, Shore	Tensile Strength, psi	Elongation, %	Compression Set, %
50	25	2.1×10^9	53	916	158	13
10	5	4.2×10^8	27	1180	750	100
2.5	1.25	1.1×10^8	18	135	550	100

TABLE 47. EFFECT OF GAMMA RADIATION FROM COBALT-60 IN
CROSSLINKING (147)

Mrep	Dose ergs g ⁻¹ (C)	Modulus		Molecular Weight Between Crosslinks, Mc			Moles of Links/CC x 10 ⁵
		Initial	Limiting	Initial	Limiting	Swelling	
25	2.1×10^9	121	121	3,300	3,300	2,380	17.2
5	4.2×10^8	28.6	12	13,850	32,600	8,470	1.77
1.25	1.1×10^8	15.3	3.9	26,500	102,000	19,300	0.56

The properties of radiation-cured silicone rubber were compared with a peroxide-cured compound by Ossefort, Rock Island Arsenal Laboratory⁽¹⁴⁷⁾. Table 48 shows that tensile values on some of the irradiated compounds exceeded values obtained on the peroxide-cured control. Since both the peroxide- and irradiation-cured compounds have such excellent low-temperature properties, no conclusions can be drawn regarding these except to say that radiation curing does not seriously impair these properties. Oil resistance is greatly improved in this compound upon irradiation. Work is currently under way at the Arsenal Laboratory to verify this improvement in oil resistance.

Data for an electron-vulcanized sample and a normal peroxide-cured sample are compared in Table 49.⁽¹⁴⁶⁾ The data show that, in a peroxide cure, crosslinking predominates. On the other hand, the radiation-cured sample is free of vulcanizing-agent fragments and shows no progressive cure when aged 24 hours at 250 C. However, it does show some chain scission. Warrick states that, at high temperatures, water and carbon dioxide cause chain scission and therefore their effect must become increasingly important to be taken into consideration.

Warrick indicates that the data for compression set show that radiation-cured samples have improved properties at high temperature. He states that both crosslinking and stress relaxation contribute to what amounts to a "remolding" at 150 C. Again, in Table 50, a radiation-cured sample is compared with a peroxide-cured sample of the same formulation.

Most crosslinking or chain scission is eliminated by radiation cure. But, the slight effect which does occur may be the result of changes in polymer-filler interaction. Table 51 illustrates the fact that polymer-filler interactions at high temperatures are important. The sample contained 50 parts of Micronex beads. It is possible that reactions occurring at the surface of the carbon-black particles are responsible for this marked high-temperature cure. Inert fillers are to be desired for high-temperature uses of silicone rubbers.

Harrington at General Electric studied the effect of filler loading on radiation stability⁽¹⁰⁰⁾. In his tests he used Union Carbide Corporation's K-1040 series and General Electric's SE-300 series. The chemical composition of these materials was not known, but it is known that the materials in each series differ only in the amount of filler they contain. The lower the compound number, the less filler and softer the compound contains. Table A-83 lists the changes occurring in the two series of materials with varying filler loading and varying postcures. Figures in the table indicate that the ultimate change in all the properties of these materials is such that, given a sufficient amount of radiation exposure, each of the properties will approach the same value. For example, the actual values of hardness, tensile strength, and elongation for K-1046R, K-1047R, and K-1048R are very similar at an exposure of 8.7×10^9 ergs g^{-1} (C) (1×10^8 roentgens) even though the original values differ significantly. Harrington comments that this fact also holds true for SE-361, SE-371 and SE-381. This work was particularly significant because it showed that materials cannot be improved to any great extent simply by compounding to a softer material. This procedure would be advantageous, however, in preparing compounds to be used in applications requiring a relatively low exposure.

Newell at Convair⁽¹⁴⁰⁾ has conducted screening tests on 23 silicone rubbers, irradiated at three temperatures and four fluxes. The materials found to be the most radiation resistant are Silastic 7-170, SE 381, Silastics 2048 and 80, and GE 81641.

TABLE 48. PHYSICAL PROPERTIES OF RADIATION-CURED SILICONE COMPOUNDS COMPARED
WITH PEROXIDE-CURED SILICONE (Z41C1)(145)

Property	Radiation Dose, Ergs G ⁻¹ (C) Roentgens		Peroxi- de cure		Z41C1		Z41C3R		Z41C3R1		Z41C3R2		Z41C3R3	
Tensile, psi					380		235		420		480		435	
Elongation, %					230		180		150		120		70	
Hardness, Shore A					36		43		47		52		66	
Compression Set, 70 Hr/212 F, %					12		14		20		28		32	
Low-Temp Flex, ASTM-D1045, T200F					Below -93		Below -93		Below -93		Below -93		--	
Brittle Point, ASTM-D746, F					Below -85		Below -85		Below -85		Below -85		--	
Air Oven Aging 70 Hr/212 F														
Tensile, psi					--		365		285		390		51	
Elongation, %					--		175		130		130		10	
Hardness, Shore A					--		47		45		58		6	
ASTM #3 Oil/70 Hr/212 F														
Hardness					25		48		61		64		6	
Volume Change, %					72		54		47		36		4	
DOS/70 Hr/212 F														
Hardness					--		41		55		60		5	
Volume Change, %					--		60		43		40		4	

TABLE 49. EFFECT OF AGING PEROXIDE-CURED AND RADIATION-CURED RUBBERS (2-MEV ELECTRONS)⁽¹⁴⁶⁾

Cure	Property	As Cured	Aged 24 Hr at 250 C
Radiation	Tensile, psi	876	672
	Elongation, %	580	486
	Shore	29	26
Peroxide	Tensile, psi	1088	1045
	Elongation, %	587	309
	Shore	41	55

TABLE 50. EFFECT OF RADIATION DOSE ON COMPRESSION SET OF SILICONE RUBBERS (2-MEV ELECTRONS)⁽¹⁴⁶⁾

Dose		Compression Set, %
Mrep	ergs g ⁻¹ (C)	
Peroxide cure		100
2	1.7×10^8	100
6	5.1×10^8	25
10	8.5×10^8	26
20	1.7×10^9	2
40	3.4×10^9	13

TABLE 51. EFFECT OF AGING RADIATION-CURED, CARBON-BLACK-FILLED SILICONE RUBBERS (2-MEV ELECTRONS)⁽¹⁴⁶⁾

	As Cured	Aged 24 Hr at 250 C
Tensile, psi	787	542
Elongation, %	435	115
Shore	35	75
Compression Set, %	95	--

Results are given in Table 52. There was a definite correlation between filler content and damage, the per cent damage varying inversely with per cent filler.

Another possible method for improving the radiation resistance of silicones is by the incorporation of antirads. Warrick⁽¹⁴⁸⁾ states that silicone elastomers show as much resistance to radiation as does natural rubber containing no antirads. The obvious step of improving standard formulations of silicone rubbers by using antirads is not possible, however, because peroxides and benzoyl and its derivatives, do not vulcanize dimethyl polysiloxanes in the presence of many antirads.

Two curing systems permitting the use of antirads have been used by Dow Corning Corporation. One of these is a sulfur cure similar to that used with natural rubber. The other and more practical curing system is based on dimethyl polysiloxanes containing less than 0.5 mole per cent methylvinyl siloxane units cured with di-*t*-butyl peroxide. Antirads may be incorporated into this system by slightly raising the amount of peroxide curing agent. Recently, they have developed new polysiloxane polymers and special formulations which are 25 times more radiation resistant at high temperatures than polydimethyl siloxane systems⁽¹⁴⁴⁾. New fillers indicate increased radiation resistance of 200 per cent in the 200 C evaluations, and the use of antirad additives gives 200 to 400 per cent more radiation resistance. Maximum limits of radiation resistance in this new family of polymers are now being studied.

Fluorosilicone elastomers, such as Silastic LS-53, on irradiation liberate a corrosive gas (HF) which causes corrosion of metals.

It was found by Fainman⁽¹⁰³⁾ that the only reliable seal material in a radiation environment of 3×10^8 ergs g^{-1} (C) in contact with oil at 450 F was a silicone gasket. The commercially available gasket used was Silastic 50-24-480. It retained its physical properties to 10^9 ergs g^{-1} (C) at room temperature. It was utilized in a WADC deposition tester for a total of 48 to 50 hours, where it was exposed to temperatures of 450 F and exposure doses of 1.2×10^9 ergs g^{-1} (C).

The dielectric properties of silicones are little affected unless absorbed doses exceed 2×10^{10} to 5×10^{10} ergs g^{-1} .⁽⁴⁹⁾

Because of the many desirable properties, particularly heat and radiation resistance, silicone rubber is being specified for control and power cables used with atomic equipment.

Cyanosilicone Elastomers

The cyanosilicone elastomers are a new family of compounds formed by copolymerizing gamma-cyanopropylmethyl siloxane with dimethyl siloxane and a small but significant amount of vinylmethyl siloxane.⁽¹⁴⁹⁾ The addition of the vinyl groups gave physical properties similar to those of dimethyl silicone gaskets. The presence of the cyanopropyl group improved the resistance of these elastomers to low temperatures and the effects of radiation and lowered the oxygen permeability. The radiation resistance of the cyanosilicone elastomers, as compared with that of dimethyl silicone, is shown in Table 53.

TABLE 52. RADIATION RESISTANCE OF SOME SILICONE COMPOSITIONS⁽¹⁴⁰⁾

Material	Class	Manufacturer	Damage at 10^{10} Ergs G^{-1} (C), per cent change			
			Elongation	Tensile	Tear	Hardness
Silastic 7-170	Low compression stock Dimethyl 24/480 post cure Gum, 52.5% Silica, 48.0%	Dow Corning	-45	+38	-20	+38
SE-381	Low compression Methyl vinyl 24/480 post cure SE 33 gum, 43% Silica, 57%	General Electric	-20	0	-43	+14
Silastic 2048	General purpose Dimethyl and phenyl methyl 24/480 post cure Gum, 83.5% Silica, 33.6%	Dow Corning	-70	+47	-40	+28
Silastic 80	Dimethyl 24/480 post cure 401 Gum, 60.1% Silica, 32.1%	Dow Corning	-70	-4	-75	+12
B1641 (SE 442)	Low compression Methyl vinyl 24/480 post cure SE 33 gum, 50% Silica, 41%	General Electric	-80	-8	-80	+16
Y-1031	Low temperature methyl phenyl, 10% phenyl 24/480 post cure Gum, 58% Silica, 31%		-30 ^(a)	0 ^(a)	-18 ^(a)	+17 ^(a)
LS 53	Fluorinated silicone 24/300 post cure Gum, 76.9% Silica, 22.3%		-76	-86	-70 ^(b)	+35 ^(c)

(a) Irradiated only to 5×10^7 ergs g^{-1} (C).

(b) Estimated.

(c) Softens and then hardens.

TABLE 53. RADIATION RESISTANCE OF CYANOSILICONE ELASTOMERS

Change in Physical Properties During Exposure to 1×10^9 Ergs G ⁻¹		
	Cyanopropyl Silicone	Dimethyl Silicone
Durometer Change, units	0	+30
Tensile Change, %	-15	-35
Elongation Change, %	-24	-85

Fluorocarbon Rubbers

The fluorocarbon rubbers, in general, do not have the radiation stability desired for nuclear applications. However, because of their chemical and heat resistance, efforts are being made to either improve their radiation resistance or to determine how they might be used. A summary report on fluorocarbons was published by the REIC during 1959. (150)

Viton A, a copolymer of hexafluoropropylene and vinylidene fluoride, has become one of the most important elastomers for applications requiring resistance to diester fluids and to high temperatures. Harrington⁽¹²⁷⁾, studying the effect of filler on this material, incorporated 20, 40, and 60 parts of carbon black into Viton A compounds, but found no improvement in radiation stability. Original tensile-strength values varied with the amount of carbon black. After an exposure dose of 8.7×10^9 ergs g⁻¹ (C), the final tensile strength values correlated more with the original values than with differences in radiation stability. Data are given in Tables A-84 and A-85.

The effect of five antirads with Viton A was examined. (51) The antirads used were Akroflex C (35 per cent N-N'-diphenyl-p-phenylene diamine plus 65 per cent phenyl-alpha-naphthylamine), naphthylamine, naphthol, FLX (N-phenyl-N'-o-tolyloethylene diamine), and anthraquinone. No improvement in radiation stability was noted.

Radiation-induced compression set was determined for room temperature in air and in alkyl diphenyl ether (C₁₄-C₁₆). (51) Little difference was observed due to the type of environment. The average compression set was 95 to 99 per cent.

The effects of temperature and radiation were investigated at Convair. (17) Viton A was irradiated to a total exposure dose of 1.74×10^9 ergs g⁻¹ (C) at 0, 73, and 350 F. An appreciable decrease in tensile strength occurred when the specimens were irradiated and tested at 350 F. This decrease did not occur when the specimens were irradiated and tested at 0 and 73 F. This is in agreement with work done at General Electric⁽¹⁵¹⁾ which showed that Viton A possessed very poor stability when irradiated in air at temperatures higher than about 250 F. At 350 F, the elongations of the irradiated and control specimens were approximately the same. At 0 and 73 F, there was a decrease in the elongation of the irradiated specimens. This decrease was more definite at 73 F than at 0 F.

Viton A does not degrade as rapidly when immersed in argon or jet turbine oil at 400 F as when irradiated in air. (152) Table 54 shows the change in tensile strength, elongation, and hardness for Viton A irradiated in air, argon, and a jet turbine oil. No reason for this retardation has been advanced at the present time. It would appear, however, that Viton A might be used for seals or gaskets in a radiation environment when immersed in oil.

TABLE 54. PROPERTY CHANGES IN VITON A^(a) IRRADIATED IN AIR, ARGON, AND JET TURBINE OIL AT 400 F BY CORAL F-60⁽¹⁵³⁾

Environment	Radiation Dosage, ergs g ⁻¹ (C)	Physical Properties ^(b)		
		Tensile Strength, psi	Elongation, per cent	Hardness, Shore
Air	0	1044	192	66.2
Air	8.7×10^7		Disintegrated	
Argon	2×10^8	2145	172	72
Argon	5×10^8	742	61	76
Mil-L-7808 Oil ^(c)	8.7×10^7	1112	208	64.8
Mil-L-7808 Oil	4.4×10^8	1028	211	64.4
Mil-L-7808 Oil	1.7×10^9	961	117	64.8

(a) Viton A is the trademark for a Du Pont fluororubber.

(b) Samples were tensile dumbbells.

(c) Mil-L-7808 Oil is a synthetic diester jet turbine oil.

A modification of Viton A, known as Viton B or LD-234, has been found to have improved resistance to red fuming nitric acid and to radiation. (154) Viton A, Viton A-HV, and Viton B (LD-234) were irradiated in bis-phenoxy-phenyl-ether at 400 F to an exposure dose of 10^{10} ergs g⁻¹ (C). Viton B was about twice as radiation resistant as the other two types. Tensile strength decreased only from approximately 2600 to 2400 psi while elongation decreased by approximately 50 per cent. Two Viton B sealant formulations⁽¹⁵⁵⁾ were exposed to 10^{10} ergs g⁻¹ (C). These showed an increase in tensile strength, but elongation decreased considerably. Data are given in the section on sealants. O-rings have been incorporated as components in hydraulic systems, but irradiation data are not yet available.

Kel-F shows the poorest stability to radiation. It reaches threshold damage at less than 3×10^8 ergs g⁻¹ (C) and is damaged by 25 per cent at approximately 6×10^8 ergs g⁻¹ (C). It becomes soft and tacky at the above doses⁽¹⁰⁰⁾ However, it has been noted that Kel-F elastomer is stable in silicone ester fluids at room temperature to 1×10^{10} ergs g⁻¹ (C). This suggests that stability depends on operation media, and stability in air cannot be regarded as an indication of its capability under actual operation.

Information by Wall, et al., (154), shows that Kel-F Elastomer 3700 crosslinks rapidly at exposure doses below 1×10^9 ergs g⁻¹ (C); at 1.4×10^9 ergs g⁻¹ (C) degradation begins to dominate.

Table 55 shows data for a variety of Viton A and Kel-F 5500 Elastomers. (114)

Results for a fluorobutyl acrylate elastomer⁽⁶⁷⁾ are shown in Table 56. For this elastomer, the tensile strength increases by about 40 per cent, hardness increases by about 20 per cent, and elongation decreases by greater than 70 per cent at an absorbed dose of 1.1×10^{10} ergs g⁻¹.

Viton A and Poly FBA (1F4) appear to be about equal in their resistance to radiation and are similar in this respect to many of the silicone rubbers. (100) FBA

TABLE 55. EFFECT OF RADIATION ON PHYSICAL PROPERTIES OF VITON A AND KEL-F ELASTOMERS⁽¹¹⁻¹³⁾

Materials	Dose		Initial Properties and Per Cent Change						Remarks
	ergs	roentgen	Hardness,		Elongation,		Tensile Strength,		
	g^{-1} (C)	$\times 10^{-6}$	Shore A	$\Delta\%$	%	$\Delta\%$	Psi	$\Delta\%$	
Viton A-7	0	0	88		250		2270		Gray-brown (a)
	8.7×10^9	100		12.5		-94.0		6.9	
Viton A-8	0	0	79		180		2285		Tan (a)
	8.7×10^9	100		22.8		-88.9		-1.0	
Viton A-9	0	0	78		185		1810		Tan (a)
	8.7×10^9	100		24.4		-84.7		46.3	
Viton A-10	0	0	77		140		1765		Brown (a)
	8.7×10^9	100		23.4		-85.7		12.4	
Viton A-11	0	0	79		125		2095		Dark gray (a)
	8.7×10^9	100		24.1		-80.3		27.9	
Pr 1710-X69	0	0	74		180		1525		Black (a, b)
	8.7×10^9	100		23.0		-86.1		18.5	
Kel-F 6500	0	0	82		550		1810		Gray
	8.7×10^7	1		0.0		9.1		44.2	
	4.4×10^{11}	5		0.0		-8.2		19.6	
	1.0×10^{10}	22		3.2		-41.8		-28.8	
	4.8×10^9	55		16.1		-73.0		-24.0	
	8.7×10^9	100		25.8		-80.0		-13.0	

(a) Broke when bent 180 degrees.

(b) Slightly tacky.

(c) Glossy on surface, quite tacky.

TABLE 56. EFFECT OF RADIATION ON PHYSICAL AND ELECTRICAL PROPERTIES OF FLUOROBUTYL ACRYLATE RUBBER⁽¹⁴⁾

Dose					
	Thermal neutrons (nv ₀) ¹	Ergs g ⁻¹			
	None	None	0.23 x 10 ¹⁸	0.45 x 10 ¹⁸	1.73 x 10 ¹⁸
			0.58 x 10 ¹⁰	1.1 x 10 ¹⁰	4.3 x 10 ¹⁰
Density, g/cm ³		1.6387	1.6410	1.6410	1.6467
					1.6711
Weight loss, % of initial	--		0.15	0.73	2.2
					4.4
Volume Resistivity, ohm-cm	1 x 10 ¹⁰		5 x 10 ⁴	1 x 10 ⁴	800
					50
Tensile Strength, psi	1070 ± 75		840 ± 75	660 ± 40	530 ± 75
					700 ± 100
Elongation, % at break	127		46	22	8
					0
Dielectric Strength, v./mil	86		0	0	0
					0
Hardness, Shore A	71		84	86	96
					100

reached threshold damage at approximately 5×10^8 ergs g^{-1} (C) and 25 per cent damage at 10^9 ergs g^{-1} (C). Viton A reached threshold damage at 5×10^8 ergs g^{-1} (C) and 25 per cent damage at 6×10^9 ergs g^{-1} (C). Harrington states that, for dynamic applications, these materials should not be exposed to doses of greater than 1×10^{10} ergs g^{-1} (C), but they probably could be exposed to higher doses for static applications.

None of the fluoroclastomers gave evidence of radiation-induced stress cracking. (100)

Two fluorinated polyester elastomers, HA-1 and HA-2, manufactured by Hooker Chemical Company have been recommended as temperature- and chemical-resistant materials. HA-1 is based on an adipate polyester and HA-2 is based on an adipate-isophthalate polyester. Both elastomers, containing 50 parts of carbon black, were irradiated to an exposure dose of 4.3×10^{10} ergs g^{-1} (C). Changes in stress-strain properties are given in Table A-84(127). Recipes are shown in Table A-85.

It can be seen that hardness increased while both elongation and tensile strength decreased as the radiation dose was increased. Tensile strength of the HA-2 material decreased less than that of the HA-1 material. However, on the basis of flexibility after the 4.3×10^{10} ergs g^{-1} (C) exposure, the HA-1 material appeared to be in slightly better condition. Harrington found these materials to be superior to the other fluorine-containing elastomers he examined.

Ethylene-Propylene Rubber

One of the more recent rubbers which is being produced on a semicommercial basis in Europe is the ethylene-propylene copolymer marketed by Montecatini in Italy. Carbon-black (50 parts)-reinforced vulcanizates have tensile strengths of 3,500 to 4,000 psi, elongations of 450 to 500 per cent, and high moduli, 1,200 to 1,700 psi. It is a saturated rubber and, similar to Hypalon (chlorosulfonated polyethylene), has excellent outdoor-aging, sunlight, ozone, heat, acid, and alkali resistance. It has poor flame resistance and, although resistance to hydraulic fluids, it has poor resistance to aliphatic and aromatic hydrocarbons and to chlorosolvents. There are no data in the REIC files on the radiation resistance of commercial materials, but, on the basis of the work of Grace and co-workers (135), it is not expected that ethylene-propylene rubber would have good radiation resistance. Grace prepared experimental ethylene-propylene polymers and found they softened with irradiation, as does polypropylene. Losses in tensile strength and elongation were severe. The per cent set after irradiation was also relatively high.

Polysulfide Rubber (Thiokol)

Thiokol elastomers have exceptionally good resistance to many types of solvents. The service temperature range is -65 to 300 F, depending on the compounding, cure, and use. Only Thiokol ST and FA have been examined for radiation resistance. Thiokol ST is among the poorest of the elastomers with respect to radiation resistance. (133) A dose of 10^8 ergs g^{-1} (C) or slightly higher is sufficient to damage this material seriously. Thiokol ST eventually becomes fluid, as does Butyl rubber. However, to soften Thiokol requires 20 times the exposure needed to soften Butyl rubber. (76) Although radiation causes the tensile strength to increase initially, long exposure causes the strength to be decreased.

Although tensile strength decreases, it retains its elongation to a greater extent than most elastomers. (51) After an exposure dose of 1.3×10^{10} ergs g^{-1} (C), Thiokol

ST decreased in elongation from an original value of 210 per cent to 100 per cent. Thiokol FA dropped from 620 per cent elongation to 200 per cent at the same dose. These final values were better than were observed for nitrile (Hycar 1002), Neoprene GN, polyacrylic rubber (Hycar FA-21), and Butyl rubber. SBR rubber retained only a slightly greater elongation (100 per cent) than Thiokol ST at 1.31×10^{10} ergs g^{-1} (C), but less than Thiokol FA. With antirads such as alpha naphthylamine or FLX (N-phenyl-N'-o-tolyethylene diamine) for Thiokol ST or beta naphthol for Thiokol FA, ultimate elongation after 1.31×10^{10} ergs g^{-1} (C) exposure dose is in the range of 260 to 280 per cent. Thus for applications where flexibility is required without any great strength, Thiokol materials can be used. Stress-strain properties of Thiokol ST and Thiokol FA are given in Table 57.

Hardness does not change significantly up to 2.6×10^{10} ergs g^{-1} (C). At 4.4×10^{10} ergs g^{-1} (C), a Thiokol material became so badly damaged that hardness could not be measured. (114) At this exposure dose, both elongation and tensile strength were reduced to zero. The trend suggests that the material undergoes chain cleavage. No stress cracking was observed at any of the exposures.

TABLE 57. EFFECT OF RADIATION ON THE PHYSICAL PROPERTIES OF THIOKOL RUBBER⁽⁵¹⁾

Rubber	Antirad	Physical Properties	Dose, 10^9 ergs g^{-1} (C)			
			0	4.4	8.7	13.1
Thiokol ST	None	Tensile Strength, psi	990	790	686	590
		Ultimate Elongation, per cent	210	130	110	100
		100 Per Cent Modulus, psi	410	550	530	520
		Shore A Durometer Hardness	71	72	72	69
	FLX	Tensile Strength, psi	1080	720	550	510
		Ultimate Elongation, per cent	320	310	300	280
		100 Per Cent Modulus, psi	280	190	120	120
		Shore A Durometer Hardness	65	57	50	52
Thiokol FA	None	Tensile Strength, psi	990	990	730	610
		Ultimate Elongation, per cent	620	420	230	200
		100 Per Cent Modulus, psi	190	260	240	250
		Shore A Durometer Hardness	60	65	64	61
	Beta-naphthol	Tensile Strength, psi	580	410	120	150
		Ultimate Elongation, per cent	430	360	240	260
		100 Per Cent Modulus, psi	100	90	120	150
		Shore A Durometer Hardness	48	45	40	38

Compression set is greatly increased with Thiokol is compressed during irradiation. Thiokol ST has a compression-set value of 107.6 after an exposure dose of 5.23×10^9 ergs g^{-1} (C), while a dose of 1.2×10^8 ergs g^{-1} (C) is required for a 50 per cent compression set.

Thiokol rubbers are used extensively as sealants. Tests results for Thiokol sealants were discussed in the section on effects of radiation on components.

Butyl Rubber

Butyl rubber, a copolymer of isobutylene and isoprene (0.5 to 4.5 per cent), has good oxidation resistance and low permeability to air and many other gases. However, it has probably the least radiation stability of any of the common synthetic rubbers. This is due primarily to the fact that Butyl rubber undergoes very rapid chain cleavage when irradiated. It contains a quaternary carbon which has been shown to have poor radiation stability.

Butyl and its modifications, such as brominated butyl, are affected similarly with radiation. Tensile strength and hardness of these polymers decrease with increasing radiation exposures. Twenty-five per cent damage is reached for hardness at an absorbed dose of approximately 5×10^9 ergs g^{-1} , and for tensile strength and elongation at about 10^9 ergs g^{-1} . At exposure doses above 5×10^9 ergs g^{-1} (C), Butyl rubbers become soft, finally becoming similar to a grease in consistency.

There is no evidence of stress cracking. (69, 114) In general, Butyl rubbers appear suitable for use in radiation fields only for applications which involve relatively low radiation-exposure doses.

EFFECT OF RADIATION ON SPECIFIC PHYSICAL PROPERTIES OF ELASTOMERS

This section compares the radiation resistance of the various elastomers according to physical properties. The data are presented in Figures C-1 to C-8 in Appendix C.

Tensile Strength

Styrene-butadiene (GR-S), natural, and nitrile rubbers are the best elastomers for retention of tensile strength on irradiation. Tensile strength of these rubbers changes by 25 per cent only after dosages of 10^{10} to 10^{11} ergs g^{-1} (C). Bopp and Sisman found SBR (GR-S) to be the superior rubber.

Polyacrylic, neoprene, and Thiokol rubbers have approximately equal radiation stability. These three rubbers are damaged by 25 per cent at approximately 7×10^9 ergs g^{-1} (C).

Most silicone rubbers are affected by radiation at about 10^5 ergs g^{-1} (C); however, for some silicones the tensile strength does not change by 25 per cent up to approximately 5×10^9 ergs g^{-1} (C).

Butyl rubber is the poorest of the commonly used elastomers with respect to retention of tensile strength. It is damaged by 25 per cent at 2.3×10^9 ergs g^{-1} (C).

The tensile strength values at 25 and 50 per cent damage for compounded rubbers prepared by The B. F. Goodrich Company⁽¹³²⁾ and tested after irradiation appear to be lower than those reported by Bopp and Sisman for the same types of rubbers.

However, the Goodrich recipes were different from those of Bopp and Sisman. The rubbers used for the Bopp and Sisman studies contained from 40 to 75 parts by weight of carbon black, while those used for the Goodrich studies contained 20 to 50 parts by weight of carbon black. Also a cobalt-60 source was used by Goodrich instead of a reactor as was used by Bopp and Sisman. The relative order of stability with respect to tensile strength was found to be different for the elastomers by the two studies, although natural rubber and SBR (GR-S) were the best in both tests. Nitrile rubber appeared to have better radiation resistance in the Bopp and Sisman studies than in the Goodrich studies.

The Goodrich studies were not extended over as wide a range of radiation doses as the Bopp and Sisman and, as a result, threshold doses could not be determined. The doses which gave 25 per cent and 50 per cent damage are shown in Figure C-2 in Appendix C.

Elongation

In general, elongation of elastomers is the property most readily affected by radiation. Natural rubber shows the greatest stability with respect to elongation. This property is unaffected by radiation up to a dose of 7.5×10^8 ergs g^{-1} (C), and is damaged by 25 per cent at a dose of 5×10^9 ergs g^{-1} (C). Styrene-butadiene rubber (GR-S) is not so resistant to radiation as natural rubber, but is affected by doses of 2×10^8 ergs g^{-1} (C) and is damaged by 25 per cent at 1.3×10^9 ergs g^{-1} (C). Butyl rubber showed unusually good stability with respect to elongation. This would not be expected since it is generally regarded as having poor radiation stability. (112) Polysulfide rubber is the elastomer showing the poorest stability to radiation.

Elongation was determined by Goodrich (112) for compounded rubbers after test specimens were irradiated. The values obtained were in fairly good agreement with the results reported by Bopp and Sisman. These values are given in Figures C-3 and C-4 in Appendix C.

Compression Set

Recovery after 25 per cent compression is poorer for irradiated rubbers than for unirradiated materials; Butyl and Thiokol show the least recovery, though all the elastomers are affected. Thiokol and Butyl soften when irradiated, and consequently lose most of their elastic properties. Natural rubber and Hycar PA show the least change in compression set. Although the compression set of silicone rubber deteriorates initially, it improves over longer irradiation periods. (112) Data for compression set are given in Figure C-5 in Appendix C.

In a second test for determining the compression set of elastomers, the specimens were stressed during irradiation. (76) The test was made under constant deflection rather than under constant load. The results are given in Table 58. It will be noted that Hycar OR-15 (1001) is equal to natural rubber in this test, although all the elastomers had deteriorated considerably after exposure to 6.4×10^9 ergs g^{-1} (C) in the ORNL graphite reactor.

TABLE 58. RECOVERY OF ELASTOMERS COMPRESSED 25 PER CENT DURING IRRADIATION (COMPRESSION-SET TEST B)⁽⁷⁶⁾

Elastomer	Recovery, per cent			
	In Jig 190 hr		In Jig 840 hr	
	Unirradiated	Irradiated ^(a) to 1.4×10^9 Ergs G ⁻¹ (C) ^(b)	Unirradiated	Irradiated ^(c) to 6.4×10^9 Ergs G ⁻¹ (C) ^(b)
Natural rubber	93	52	90	25
GR-S 50	90	53	88	22
Butyl rubber				
GR-I	91	23	88	Tarry fluid
Neoprene W	62	20	42	12
Hycar OR-15	92	62	90	24
Hycar PA-21	92	58	91	14
Silastic 7-170	97	27	95	0
Thiokol ST	90	2	82	0

(a) 7.5 hr in reactor.

(b) Calculated.

(c) 40 hr in reactor.

Strain at 400-Psi Load

Stress-strain curves were recorded by Bopp and Sieman⁽⁷⁶⁾ for the various elastomers before and after irradiation. From these data, the elongation at 400 psi was determined for the unirradiated material and for the material after it had been subjected to various radiation doses. A Baldwin Southwark Universal testing machine was used with a Baldwin extensometer and Scott grips. For elastomers which would stretch at least 3 per cent, the speed of testing was 10 inches per minute. For materials embrittled by irradiation so that elongation was less than 3 per cent, the speed of testing was reduced in order to prevent failure by impact at the start of stressing. This speed value was not given.

The data indicating the effect of radiation on the stiffness of elastomers show natural rubber to have the greatest resistance to radiation with respect to strain at 400-psi load. This property has decreased by 25 per cent at a dosage of about 9×10^9 ergs g⁻¹ (C). Thiokol rubber, which softens upon irradiation, also retains better than 75 per cent of its original value to about 8.5×10^9 ergs g⁻¹ (C), but the elongation increases so rapidly that it changes 50 per cent by the time the dose has increased to 10^{10} ergs g⁻¹ (C). There is not much difference among the other elastomers. Silicone rubber and GR-S are probably the poorest materials with respect to their resistance to radiation as it affects strain at 400-psi stress.

Set at Break

Neoprene W, natural rubber, and SBR (GR-S) show the best resistance to radiation with respect to set at break, in the order given. There is not a great deal of difference in the radiation stability in regard to set at break among the various rubber materials.

Hardness

The most rapid changes in hardness upon irradiation are observed in Hycar OR-15, Butyl, neoprene, and Silastic rubbers. Thiokol changes at a slow rate, probably as a result of a balancing effect of crosslinking and cleavage. (112) SBR (GR-S) also changes slowly in hardness when irradiated. Although neoprene changes rapidly, it is not affected by radiation until it has received a dose of about 4×10^9 ergs g^{-1} (C), which is better than the other elastomers. According to the same data, Butyl rubber is not affected until exposed to a dosage of 2×10^9 ergs g^{-1} (C). This rubber, once it begins to soften, does so rapidly.

Dynamic Tests

There has been a lack of dynamic testing of elastomers. Such tests are extremely important for determining the proper materials for various applications in a radiation environment and more information on the effect of radiation under dynamic conditions is needed. The B. F. Goodrich Company has made some dynamic tests on rubber materials. Four of these tests have been completed and are reported in the literature. (116) These include (1) Yerzley resilience, which is closely related to hysteresis, (2) abrasion loss, (3) permanent set, and (4) Gehman freeze point. The results of these tests, given in the following sections, have been taken from the Goodrich report. (116)

Yerzley Resilience

All the rubber compounds examined, except Neoprene GN, showed an improvement in resilience on irradiation. The change was small for gum stock and carbon black-reinforced stocks of natural rubber and Neoprene GN. Natural-rubber compounds showed a 2 per cent increase. Neoprene GN compounds showed a 1 to 2 per cent decrease. Both SBR and Hycar 1002 gum rubber and carbon black-reinforced rubber compounds showed marked increases in resilience with irradiation. The increases were 52 per cent for SBR gum stock, 38 per cent for SBR black stock, 25 per cent for Hycar 1002 (OR-25, a nitrile rubber gum stock), and 23 per cent for Hycar 1002 black stock. Table 59 lists the percentage change in Yerzley resilience for these rubber stocks.

TABLE 59. CHANGE IN YERZLEY RESILIENCE WITH GAMMA IRRADIATION⁽¹¹⁵⁾Total gamma-ray exposure = 10^{10} ergs g⁻¹ (C).

Rubber	Initial Value, per cent	Final Value, per cent	Per Cent of Initial	Change, per cent
Natural rubber (gum stock)	93.8	95.5	101.9 ± 0.8	+1.9
GR-S	58.3	88.4	151.7 ± 2.3	+51.7
Neoprene GN	85.4	83.2 ^(a)	$97.5 \pm 1.8^{(a)}$	-2.5 ^(a)
Hycar 1002	70.8	88.2	124.7 ± 1.8	+24.7
Natural rubber + carbon black	74.6	76.0	101.9 ± 1.0	+1.9
GR-S + carbon black	55.5	76.5	137.8 ± 0.5	+37.8
Neoprene GN + carbon black	71.5	70.6 ^(b)	$98.8 \pm 0.8^{(b)}$	-1.2 ^(b)
Hycar 1002 + carbon black	62.1	75.6 ^(c)	$123.2 \pm 1.4^{(c)}$	+23.2 ^(c)

^(a) Total radiation exposure was 10^9 ergs g⁻¹ (C).^(b) Total radiation exposure was 3.5×10^9 ergs g⁻¹ (C).^(c) Total radiation exposure was 7×10^9 ergs g⁻¹ (C).Abrasion Loss

SBR (GR-S) and nitrile rubber-carbon black loaded stocks improved in abrasion resistance on irradiation. Natural rubber-carbon black stock remained stable up to 5.9×10^9 ergs g⁻¹ (C). Natural rubber and Neoprene GN gum stocks each underwent a loss in abrasion resistance by 89 per cent at 8.5×10^9 ergs g⁻¹ (C). The carbon black-reinforced stocks of GR-S and nitrile rubber were remarkable in that they both showed a decrease in abrasion loss with irradiation: a 28 per cent improvement for GR-S and an 89 per cent improvement for Hycar 1002. This means that the abrasion resistance of carbon black-reinforced rubber compounds of GR-S and Hycar 1002 actually improves with a radiation dose of 10^{10} ergs g⁻¹ (C) (see Table 60).

TABLE 60. CHANGE IN PICO ABRASION INDEX WITH GAMMA IRRADIATION (116)

$$\text{Abrasion index (per cent)} = \frac{\text{volume loss of standard}}{\text{volume loss of sample}} \times 100.$$

Rubber	Abrasion Index, per cent, for Indicated Radiation Dose, ergs g ⁻¹ (C)							Per Cent of Initial	Per Cent Change
	0	10 ⁸	5 x 10 ⁸	10 ⁹	3.5 x 10 ⁹	7 x 10 ⁹	10 ¹⁰		
Natural rubber (gum stock)	28.3	26.9	26.6	26.8	23.5	14.7	3.2	11.3	-88.7
GR-S	16.9	16.5	16.2	11.5	6.2	7.2	3.8	22.4	-77.6
Neoprene GN	45.0	42.0	41.7	27.5	6.0	4.9	4.8	10.7	-89.3
Hycar 1002	18.7	19.8	16.1	9.8	5.6	5.1	4.9	26.2	-73.8
Natural rubber + carbon black	96.8	96.6	97.8	94.4	90.7	85.2	68.4	70.6	-29.4
GR-S + carbon black	82.2	83.0	83.0	82.8	89.0	100.2	105.2	128.1	+28.1
Neoprene GN + carbon black	105.4	100.6	101.4	98.6	102.9	71.4	57.8	54.8	-45.2
Hycar 1002 + carbon black	70.8	70.1	72.7	86.0	101.2	163.5	133.0	187.9	+87.9

Permanent Set

In the change in permanent set with irradiation, natural rubber was far superior to the three other elastomers tested. Both its gum and carbon black-reinforced compounds had relatively low initial permanent set, and relatively little change occurred as a result of irradiation. The gum and carbon black-reinforced stocks of SBR, Neoprene GN, and Hycar 1002 (nitrile) all showed marked decreases in permanent set as a result of irradiation (see Table 61).

Gehman Freeze Point

All the gum and carbon black-reinforced rubber compounds showed small and approximately equal increases in the Gehman freeze point, ranging from 4 to 12 C, as shown in Table 62.

TABLE 61. CHANGE IN PERMANENT SET WITH GAMMA IRRADIATION⁽¹¹⁶⁾

$$\text{Permanent set (per cent)} = \frac{\text{initial height} - \text{recovered height}}{\text{initial height}} \times 100.$$

Rubber	Permanent Set, per cent, for Indicated Radiation Dose, ergs g ⁻¹ (C)							Change in Permanent Set, per cent
	0	10 ⁸	5 x 10 ⁸	10 ⁹	3.5 x 10 ⁹	7 x 10 ⁹	10 ¹⁰	
Natural rubber	2.9	3.7	3.8	3.4	3.8	3.2	2.6	-0.3
GR-S	(Too soft to test)			30.1	8.0	3.7	2.2	(Large)
Neoprene GN	40.0	41.2	36.9	15.8	2.8	1.6	(Too hard to test)	-40.0
Hycar 1002	10.2	9.8	6.6	1.7	0.6	0.3	0.3	-9.9
Natural rubber + carbon black	11.0	11.4	12.0	11.6	10.0	9.4	7.1	-3.9
GR-S + carbon black	15.8	13.9	17.4	9.9	4.7	3.4	2.0	-15.8
Neoprene GN + carbon black	27.4	28.4	24.8	13.1	(Too hard to test)			-27.4
Hycar 1002 + carbon black	11.0	11.1	8.0	1.8	0.4	(Too hard to test)		-11.0

TABLE 90. CHANGE IN GEHMAN FREEZE POINT WITH GAMMA IRRADIATION(116)

Rubber	Gehman Freeze Point, C, for Indicated Radiation Dose, ergs g ⁻¹ (C)							Over-all Change in Gehman Freeze Point, C
	0	10 ⁸	5 x 10 ⁸	10 ⁹	3.5 x 10 ⁹	7 x 10 ⁹	10 ¹⁰	
Natural rubber	-59	-58	-59	-58	-58	-56	-53	+6
GR-S	-52	-52	-52	-52	-52	-50	-48	+4
Neoprene GN	-40	-37	-38	-37	(+7)	-35	-28	+12
Hycar 1002	-23	-23	-23	-23	-23	-19	-14	+9
Natural rubber + carbon black	-57	-56	-56	-56	-56	-52	-50	+7
GR-S + carbon black	-49	-49	-49	-49	-49	-46	-45	+4
Neoprene GN + carbon black	-37	-37	-37	-36	-31	-37	-30	+7
Hycar 1002 + carbon black	-25	-24	-24	-24	-21	-19	-19	+6

Conclusions

According to the Goodrich report, dynamic tests indicate that the tendency has been to underrate the ability of rubber compounds to withstand irradiation in terms of mechanical service. Some mechanical properties of certain rubber compounds actually improve during irradiation. Thus, it is seen that it is imperative to obtain more data under dynamic conditions.

State of Cure

Studies of the effect of state of cure indicate that tighter cure retards compression set of rubbers which are irradiated in a stressed state. (155) This suggested that, contrary to the case where the rubber is generally unstressed or lightly stressed between loading cycles, rubber end-items which are subjected to continuous, appreciable compression or extension during irradiation should have the maximum cure commensurate with the required service properties. In this work, the effect of state of cure on the radiation resistance of Hycar 1001 (high acrylonitrile content) was determined. Six different cures were selected to represent undercure, optimum cure and overcure for this Altax-sulfur cured, black-loaded (50 phr of SRF) Hycar stock. An interpretation of the results indicated that the more a polymer is crosslinked before compression and irradiation, the higher the exposure dose required before chain scission or further crosslinking or both become measurable. This contrasts with earlier static stress-strain work

where it was recommended that the most tolerable undercure be used in any application to take advantage of radiation curing. That recommendation still applies in cases where the rubber material is not stressed during irradiation.

Data obtained by Born⁽¹⁵⁶⁾ confirmed earlier results which indicated that increasing cure in a compound reduces its susceptibility to radiation-induced set. On an equal hardness basis, radiation curing of Hycar 1001 offers no advantage over chemical cure regarding resistance to radiation induced compression set.

METHODS FOR IMPROVING THE RADIATION RESISTANCE OF ELASTOMERS

Several methods were attempted to improve the radiation stability of elastomers. These included the use of fillers, the addition of radiation-resistant resins, and organic additives called antirads.

Fillers, in general, improve the radiation stability of rubbers. Mineral fillers are not as good as carbon black. Bopp and Sisman⁽⁷⁶⁾ used asbestos in a natural-rubber formulation, while Born, at the B. F. Goodrich Company⁽¹³²⁾, used mica and asbestos. In general, the physical properties were inferior to the standard compositions, and there was no improvement in radiation stability.

Researchers at the Goodrich Company⁽¹³²⁾ evaluated Goodrite Resin 50 (a high styrene-butadiene copolymer) in GR-S, Durez (a phenolic) in nitrile rubber, and Hycar HH (a brominated Butyl rubber which is more compatible than Butyl rubber) in natural rubber. These materials improved the radiation resistance of the gum stocks, but they appeared to have little effect on black stocks.

Improvement of the radiation resistance of rubber compositions was obtained by adding organic additives similar in nature to antioxidants (antirads).⁽¹³²⁾ A number of antirads were uncovered that extended the retention of tensile strength and the ultimate elongation of natural-rubber tread stock under irradiation by a factor of ten. The best antirad, N,N'-cyclo-hexylphenyl-para-phenylenediamine, resulted in the retention of 99 per cent of the initial tensile strength and 88 per cent of the ultimate elongation at a dose of 10^{10} ergs g⁻¹ (C), compared with 36 and 18 per cent, respectively, for the normally protected control rubber compound.⁽¹¹⁶⁾ Table 63 lists the ten best antirads for natural rubber, based on retention of tensile strength and elongation.

Antirads appear to be the only method that gives any real improvement to radiation resistance of diene-type elastomers. Antirads have improved the radiation stability of natural rubber by a factor of two to ten. Work is in progress to determine the improvement shown by antirads with other elastomers. Additions of fillers, reinforcing agents, crosslinking materials, plasticizers, and resins have some effect on particular types of polymers, but the antioxidant-type compounds (antirads) have the greatest effect. Antirads are, however, specific in that some are more effective with one type of polymer than with another. Thus far, over 100 materials have been evaluated as potential antirads by The B. F. Goodrich Co. This work shows that best results are obtained if the antirad is utilized in combination with the commonly used antioxidant phenyl beta naphthyl amine. Table 64 lists some of the more effective antirads and corresponding elastomers that are improved.

TABLE 63. RELATIVE RATING OF ANTIRADS BASED ON STRESS-STRAIN PROPERTIES(116)

Total radiation exposure = 10^{10} ergs g^{-1} (C).

Relative Rating	Antirad	Per Cent of Initial Value	
		Tensile Strength	Elongation
1	N,N' -Cyclohexylphenyl-p-phenylenediamine	99	88
2	35% Diphenyl-para-phenylenediamine, plus 65% phenyl-alpha-naphthylamine	86	76
3	Quinhydrone	91	74
4	N-p-tolyl-N' -p-toluenesulfonyl-p-phenylene-diamine	91	70
5	N-phenyl-N' -o-tolylenethylenediamine	83	72
6	Beta-naphthol	85	71
7	Beta-naphthylamine	85	70
8	20 CC 59A	72	82
9	Pyrogallol	100	66
10	Phenyl hydroquinone	87	68
11	N,N' -Diocetyl-para-phenylenediamine	82	69
89	(ASTM natural-rubber tread-stock control)	36	18

TABLE 64. THE BEST ANTIRADS FOR VARIOUS ELASTOMERS⁽¹⁵⁶⁾

Elastomer	Best Antirads	
	Taken at 50% Loss of Original Ultimate Elongation	Taken at Loss of Original Ultimate Elongation at 1.3×10^{10} Ergs G ⁻¹ (C)
Natural rubber	Antiox 4010 ^(a)	Antiox 4010
Styrene butadiene rubber (SBR 1500/1501)	Alpha-naphthylamine	Alpha-naphthylamine
Nitrile rubber (Hycar 1002)	Alpha-naphthylamine	Quinhydrone and FLX
Neoprene GN	Akroflex C ^(b)	Akroflex C
Hypalon "20"	Quinhydrone	Quinhydrone
Polyacrylic rubber (Hycar PA-21)	FLX ^(c)	Alpha-naphthylamine
Polyamide rubber (Thiokol ST)	FLX ^(c)	FLX
(Thiokol FA)	FLX ^(c)	Buta-naphthol
Butyl rubber	None found satisfactory	None found satisfactory

(a) Antiox 4010 = N-cyclohexyl-N'-phenyl-p-phenylene diamine.

(b) Akroflex C = 35% N-N'diphenyl-p-phenylene diamine plus 65% phenyl-alpha-naphthyl amine.

(c) FLX = N-phenyl-N'-o-tolylethylene diamine.

Born⁽¹⁵⁶⁾ determined the effect of the acrylonitrile content on compression set in nitrile-butadiene and styrene-butadiene rubbers containing antirads. There appeared to be a slight increase in radiation resistance with increasing acrylonitrile content, even more so in the presence of Antiox 4010 (N-cyclohexyl-N'-phenyl-p-phenylene diamine) as an antirad.

The addition of 3 phr of an antirad slightly increased the tensile strength of the NBR compound but caused a mild decrease in the tensile strength of the 90/10 NBR/SBR compound. Little or no further change occurred in tensile strength when 5 phr of antirad was added to the base compounds.

In general, the incorporation of an antirad had little or no effect on hardness. It caused a 25 per cent decrease in volume swell in the NBR samples but no significant change in this property for the NBR/SBR samples.

Ultimate elongation increased with antirad concentration in the control compounds by amounts ranging from 18 to 58 per cent of the initial values. The increase was greater for the NBR "100" series than for the NBR/SBR "200" series.

Addition of antirad progressively decreased modulus values of both control compounds by amounts ranging from 20 to 38 per cent. The effect of antirad concentration on compression set prior to irradiation was mixed. Antiox 4010 decreased compression set of the NBR/SBR control compound by 25 per cent of the initial value, whereas

hydroquinone caused a 25 per cent increase for the NBR control. In other cases, the antirads caused little or no change.

With the above understanding of how antirad addition affected preirradiation properties, let us consider what protection the antirads afforded against radiation damage. They slightly inhibited decrease in tensile strength and caused 22 to 33 per cent less decrease in the initial ultimate elongation value by the 1×10^{10} ergs g^{-1} (C) radiation exposure dose. Only hydroquinone failed to protect against loss of elongation at break. With the exception of Antiox 4010 and FLX, antirads had little net influence on radiation-induced decreases in volume swell. However, Antiox 4019 reduced the net decrease in volume swell by 33 per cent of the difference in the NBR case and 22 per cent in the NBR/SBR case.

The most striking protection occurred in the cases of 100 per cent modulus and compression set, which along with hardness and resistance to swell and chemical attack are the most important in O-ring performance. The antirads reduced the per cent increase in modulus by amounts ranging from 21 to 50 per cent of the control-sample change in the NBR/SBR series, with Antiox 4010 being the most effective. The antirads effected moderate inhibition of modulus change in the NBR series (29 per cent), with hydroquinone giving no protection at all. In the NBR series the inhibition of compression set ranged from 38 per cent less than the radiation-induced change in the case of FLX to complete protection in the case of Antiox 4010 (no radiation-induced change in compression set). Whereas the control samples underwent a 39 per cent decrease in the compression-set value because of the 1×10^{10} ergs g^{-1} (C) dose in the NBR/SBR series, the samples containing antirads exhibited little or no change in compression set by irradiation.

Antirads protect even such specialty rubbers as these proprietary compounds, which were developed to have maximum resistance to aircraft nonradiation operating environments, from radiation damage. Second, the results repeatedly suggest strongly that compounding variables, such as type of elastomer and identity and concentration of antirad can critically influence the radiation service of premium O-ring seals for aircraft. These two conclusions point in turn to a fact that is being demonstrated with increasing frequency and force: at this state of the art, an antirad cannot casually be selected or compounded into a rubber formulation. Success in achieving radiation protection depends upon choice of a proper antirad for a particular elastomer which is specified and an educated compounding of the elastomer to produce that rubber designed to retain best the most critical service properties for the chosen application during irradiation.

In addition to the antirad studies, Born⁽¹³¹⁾ has found that, for maximum resistance to radiation, it is best to utilize elastomeric compositions in slightly undercured state. Table 65 shows that slightly undercured compositions are more stable to radiation than those highly vulcanized.

TABLE 65. EFFECT OF CURE ON RADIATION STABILITY OF NATURAL RUBBER⁽¹³¹⁾

State of Cure	Additive, phr	Per Cent of Initial Property Retained After Indicated Exposure, 10^9 Ergs G^{-1} (C)														
		100% Modulus					Tensile Strength					Elongation				
		0.87	3.0	6.1	8.7	21.8	0.87	3.0	6.1	8.7	21.8	0.87	3.0	6.1	8.7	21.8
Slight undercured	None	140	180	280	360	--	94	96	89	83	28	91	84	72	54	16
	PBNA 0.6	200	160	300	350	650	96	100	92	80	33	92	85	67	52	17
	PBNA 1.0	80	200	300	360	600	105	101	91	76	29	98	90	70	55	18
	PBNA 2.0	80	210	280	320	650	101	99	92	81	30	95	87	72	62	20
	PBNA 4.0	167	178	233	311	666	101	103	83	82	41	94	83	75	62	23
Optimum cure	None	113	180	246	280	--	99	98	55	59	30	91	71	37	37	17
	PBNA 0.6	114	193	239	307	443	104	97	82	65	39	95	75	56	42	20
	PBNA 1.0	121	193	271	342	--	105	97	83	62	39	97	79	60	40	18
	PBNA 2.0	120	173	203	273	447	102	97	82	75	37	93	80	5	51	19
	PBNA 4.0	114	161	214	271	450	102	99	82	62	51	88	83	65	55	28

Shelberg and Gevantman⁽¹⁵⁸⁾ investigated several additives as possible antirads, but none were as effective with natural rubber as Antiox 4010. Table 66 lists the materials tried, the reason for their selection, and their crystalline longevity relative to the standard, natural rubber. This latter property was determined from curves of diffraction spot intensity versus irradiation time. Samples 10 to 12 mils thick were stretched to an elongation of 400 per cent and clamped. They were then irradiated while stretched and the crystallinity checked periodically by X-ray diffraction. The radiation time at which crystallinity disappeared was compared with that for the standard rubber.

From the results of this work it was concluded that resonance and large molecular size do not necessarily provide antirad protection. Similarly, the presence of chemically stable and radiation-stable ingredients in a vulcanizate does not in itself impart protection against radiation. Also, an antirad effective for one material is not necessarily satisfactory for another, somewhat similar material.

The rubber laboratory at the Rock Island Arsenal, under the direction of Z. T. Onsefort⁽¹⁵⁹⁾, investigated potential antirads for nitrile rubber. Approximately 25 potential inhibitors of radiation damage and 3 curing systems were examined. None of the additives, with the possible exception of 2,5 ditertiary butyl hydroquinone, retarded radiation damage. The results for the ditertiary butyl hydroquinone were not conclusive, and more work with this additive is in progress.

Other means for improving radiation resistance is through modification of the elastomer. Grace and coworkers⁽¹³⁵⁾ noted that alpha methyl styrene showed promise as a component for radiation-resistant elastomers. A butadiene-methylstyrene copolymer with 35 parts of an HAF Black showed only a 2 point change in hardness after 10^{10} ergs g^{-1} (C). However, more work is needed with this type polymer to fully establish its merit in use with radiation.

In studies leading to the development of elastomers with superior resistance to degradation by nuclear radiation, Stanley and Delman⁽¹³⁰⁾ critically examined the structural changes occurring in irradiated SBR polymers. Chemical changes in SBR in toluene solutions subjected to 8.46×10^7 to 8.46×10^9 ergs g^{-1} (C) (1 to 100 megareps) of gamma radiation were followed by infrared spectrophotometric techniques. Data were

TABLE 66. EFFECTIVENESS OF ANTIRADS IN NATURAL RUBBER (158)

Antirad	Reason for Choice	Relative Crystalline Longevity(a)
N-cyclohexyl-N'-phenyl-p-phenylenediamine (Antiox 4010)	Known to be good antirad for natural rubber	4.0
Indocarbon CL	Resonance considerations and possibility of chemical combination with rubber during vulcanization	1.6
Immedial New Blue		0.89
Carbanthrene Khaki 2G	Resonance considerations and large molecular size, conceivably conducive to maximum delocalization of energy received from substrate	1.2
None	Determine effect of carbon; this sample contained no carbon	1.1
None	Standard natural rubber sample	1.0
Graphite	Radiation stability, potential resonance stability, and because it provides an infinite network of condensed rings	0.74
Copper phthalocyanine	Resonance considerations, excellent thermal, chemical, and radiation stability	0.45
Phthalocyanine		0.69
Didodecyl selenide	Reported as retarding radiation damage in lubricating oils	0.55

(a) Crystalline longevity is the ratio of the irradiation time for the stretched rubber to lose its crystal structure and the time for a standard natural rubber sample to lose its crystal structure when irradiated under the same conditions.

obtained indicating a marked differentiation between the rate of attack of trans-1,4 double bonds and that of cis-1,2 unsaturation, with the latter predominating. The findings suggest a means of inhibiting degradation of the polymer by modification of the structure at the sites most susceptible to attack. Toward this end, polymer synthesis and grafting studies based on these observations are under way in a continuation of this work.

The technique described for ascertaining specific weak points in SBR can be extended to other polymer systems to enable determination of those structures and steric configurations which impart maximum radiation resistance. This is being used as a basis for subsequent synthesis studies in this work.

Work along the lines of the cyanosilicone elastomers is being carried out by Stanford Research Institute in the preparation of fluorinated arylene modified polysiloxanes, and by the Yarsloy Research Laboratories in London in the preparation of arylene modified silcarbanes. (160)

Information regarding methods for improving elastomers can be summarized as follows:

- (1) Carbon-black stocks, in general, show somewhat better radiation resistance than their pure gum counterparts. The type of carbon black used is of little significance.
- (2) Compounds loaded with hydrated silica appear to have slightly greater radiation resistance than any of the black-loaded compounds when tested after irradiation of 2.62×10^9 ergs g^{-1} (C) (3×10^7 roentgens).
- (3) Elastomeric compounds having large loadings of heavy metal fillers are generally not improved in radiation damage in respect to tensile properties. Only lead sulfide in pure gum compounds and titanium hydride in pure gum and black compounds showed merit. Since elements of higher atomic number absorb more gamma radiation, it might be advantageous to eliminate heavy metals from a rubber formulation. The elements in rubber are predominantly of low atomic number. In general, the zinc in zinc oxide and the heavy metals in accelerators and fillers are the only exceptions. Tests are in progress to develop a satisfactory stock with magnesium oleate or potassium oleate in place of zinc oxide and stearic acid. Such a compound would have good physical properties and would be relatively transparent to gamma rays.
- (4) The addition of boron to a rubber compound improves it as a neutron shield, but the boron accelerates radiation damage. Using five parts boron by weight for 100 parts rubber, a 25-fold acceleration was observed for natural rubber, and a 14-fold increase for polyisobutylene.
- (5) Blended pure gum stocks, which contain a high polymer in addition to the elastomer have improved radiation resistance. GR-S/Goodrite 50 gum stock showed essentially no change after receiving 6.1×10^9 ergs g^{-1} (C) (1×10^7 roentgens). Hycar/Durez resin compound improved in tensile strength during irradiation while showing small changes in ultimate elongation and 100 per cent elastic modulus. Smoked sheet/Hycar III pure gum showed excellent retention of all

measured properties and GR-S/Ilycar III also showed good resistance. Ilycar III, a brominated butyl rubber, helps the blend to resist change in 100 per cent modulus and has a slightly beneficial effect on other stress-strain properties. The addition of carbon black prevents improvement in stress-strain properties with the exception of the modulus.

- (6) Certain chemicals, when added to rubber compounds, extend the retention of tensile strength and ultimate elongation in a radiation field by as much as ten times. This protective mechanism can be outlined briefly as follows:
 - (a) Reducing or nucleophilic agents prevent oxidation of the primary material. Among these agents used are: quinhidrone, pyrogallol, p-quinone, and cysteine.
 - (b) Oxidizing or electrophilic agents prevent radiation of the primary material. Included in this class are: iodine, bromine, potassium permanganate, lead tetracetate, and hydrogen peroxide.
 - (c) Buffer additives prevent a change in acidity or alkalinity which might affect critical properties. There are buffers for nearly every pH range. Examples are: citrates (sodium citrate), phthalates (potassium acid phthalate), and borates (boric acid).
 - (d) Aromatic ring systems may act as "energy sponges". They have sufficient resonance energy to hold together until the vibration-rotation energy is dissipated as heat. They usually require a side group which acts as a "point of entry" of the energy. A few examples are: terphenyl, ethyl benzene, amino benzoic acid and diphenyl amine.
 - (e) Stable free radicals provide protection for a primary material by "taking up" free radicals or activated molecules produced by radiation, thus preventing excessive gassing or further chemical reactions. Two examples of such stable free radicals are: α, α' -diphenyl- β -picryl hydrazyl, and triphenyl methyl.
 - (f) If a molecule has been equipped with a weak bond located in a noncritical place the energy from radiation absorption will go into breaking this bond rather than an important structural bond. For example, C-I side bonds on a -C-C-C- chain, or C-S instead of C-F or C-C-C- in sulfur impregnated Teilon.
 - (g) Properties dependent upon crosslinking may be promoted in polymers under irradiation by the addition of compounds such as, divinyl benzene, sulfur, or organic peroxides.
 - (h) There are substances which readily form rings, both aromatic and non-aromatic. Chelation compounds are an example. Typical of such compounds are: phenylene diamine, ethylene diamine, benzyl methyl glyoxime, salicylaldehyde, and S-2-amino ethyl isothio uranium bromide.

- (i) Some fillers reduce radiation damage in elastomers and polymers.

Since they have enormous surface areas it is believed that the mechanism involved is surface catalysis of recombination processes, or surface adsorption of electrons or ions produced by irradiation. Commonly used fillers are: asbestos, mica, clay, zinc oxide, magnesium oxide, lead oxide, powdered iron, and powdered tungsten.

Plastics

Plastics are, in general, equal or superior to the elastomers in radiation resistance, with the rigid types being the most resistant. Among the thermosetting resins, the glass fiber- and asbestos-filled phenolics, aromatic-cured epoxies, and polyurethanes are the most resistant. Of the thermoplastics, polystyrene and polyvinyl carbazole are equally as resistant to radiation, but have much lower strength and heat resistance.

The fluorine-containing plastics, such as Teflon, Kel-F, or PVC degrade in a radiation environment and liberate halogen acid which has corrosive effects on adjacent components. Gassing of most plastics is a problem in enclosed or poorly ventilated systems.

Mineral fillers and ceramic fibers improve the radiation resistance of most plastics. However, little success has been achieved with organic scintillators, except with 2,5-diphenyloxazole, which improved the radiation resistance of an epoxy adhesive by a factor of four.

Thermosetting Resins

Phenolics. Unfilled phenolics stand fairly low in radiation resistance; 25 per cent damage is accrued at an absorbed dose of 1.1×10^9 ergs g⁻¹ (C). Their tensile and impact strengths decrease about 50 per cent at 3×10^{10} ergs g⁻¹ (C). When irradiated, they swell, become very brittle, and tend to crumble. In addition, a soluble product is formed which causes the material to disintegrate in water. (81)

The addition of fillers, particularly mineral fillers, increases the stability of phenolics. Phenol-formaldehyde with asbestos filler (Haveg 41) shows excellent radiation stability, being one of the more radiation-resistant plastics. It is unaffected by radiation dosages of 3.9×10^{10} ergs g⁻¹ (C) and is damaged by 25 per cent at a dosage of 3.9×10^{11} ergs g⁻¹ (C). It may be noted that such combinations also have higher heat stability. Of interest is the fact that asbestos improved the radiation resistance of phenolics but did not improve stability of rubbers.

Micher⁽⁷⁵⁾ reported no obvious mechanical deterioration in a Bakelite phenolic impregnated with phosphorus after being irradiated for a period of 10 months in the Clinton reactor operating at full power. He claims that this performance was unequalled by any of the other materials examined. The dosages were not given for these experiments.

Phenolic laminates tested by Keller⁽⁹⁾ had not reached threshold damage after a room-temperature exposure to 8.3×10^{11} ergs g^{-1} (C). Even after the irradiated laminates were heated for 1/2 hour at 500 F, flexural strengths were high, approximately 47,000 psi. These values were equivalent to the flexural strength of nonirradiated laminates exposed to 500 F for 1/2 hour (see Table 19).

Phenolic laminates irradiated to an exposure dose of 2.1×10^9 ergs g^{-1} (C) at temperatures of 600, 700, 800, and 900 F showed equivalent or higher flexural-strength values than laminates heated to these temperatures with no irradiation. (9,81) Keller points out that a phenolic system ordinarily deteriorates when exposed to elevated temperatures in the presence of air due to oxidation. He suggests that it is possible that irradiation inhibits the oxidation and that crosslinking takes place.

Epoxy Resins. When cured, epoxy resins are generally hard, extremely tough, and chemically inert. They are the reaction products of epichlorohydrin and polyhydroxy compounds (usually bisphenol-A) and are used as encapsulating resins for electrical parts, for protective coatings, and as binders for laminates.

These resins are above average for plastics in radiation resistance, having withstood doses up to 9.5×10^{10} ergs g^{-1} (C) without deterioration. This is very likely due to their rigidity and aromatic content. It is an example of how great rigidity can overcome the effects of the quaternary carbon atom. (112, 161)

Attkin and Ralph⁽¹⁶²⁾ summarized work on the effect of pulse radiation on cast epoxide resin systems. The samples were irradiated with a slow neutron flux ranging between 9×10^{11} and 1.2×10^{12} n $\text{cm}^{-2} \text{sec}^{-1}$, the latter figure being the maximum flux available. All results are expressed as days at pile factor 12.

Most of the flexural strengths reported consist of only one break at each level of irradiation. This is not sufficient to obtain any degree of certainty but it does indicate which are the best systems to study further. In the systems in which more than one test was carried out, it is obvious that the variance about the sample mean is increased by irradiation. This has been confirmed in later work not yet reported.

Although hardness measurements were carried out on a large number of samples, the change of hardness with irradiation was small compared with the experimental error of the measurement. Similarly the shrinkages reported were small compared with the error in measurement and the slight variation in sample thicknesses.

First results showed, as expected, that the aromatic amine hardeners produced considerably more-radiation-resistant systems than the aliphatic amines. Breakdown in these latter cases consisted of rapid fall off in flexural strength as the irradiation proceeded, and of the worst cases of formation of gas blisters in the samples.

There appears to be a connection between heat-distortion point (HDP) and radiation resistance. The rotational and flexural freedom of the methylenic structure of an aliphatic amine produces cast resins with low heat-distortion points and, conversely, the rigidity of the aromatic hardeners leads to high HGP's and increases resistance to radiation effects. The initial increases in flexural strength observed in some systems are probably caused by the reaction of the residual ethoxylane groups under the influence of radiation.

Nearly all the samples irradiated were rapidly darkened, probably due in the initial stages to conjugated unsaturation effects. The dodecenyl succinic anhydride sample was least affected in this respect. It required about 17 pile units to darken the sample through degrees of yellow and red. A side effect which should be born in mind when considering these effects is oxidation on the surface of the specimens. Reaction between the conjugated double bonds formed and oxygen diffusing into the surface of the polymer can increase the rate of chain scission, thus producing a component of degradation which will depend on sample thickness.

Diamino diphenyl methane and metaphenylene diamine are the most radiation-resistant commercially available curing agents, the former being slightly better than the latter after long irradiation periods. Benzidine appears, from the results of limited experiments, to be very much more radiation resistant than diamino diphenyl methane, due no doubt to the absence of the active methylenic link between the phenylene groups.

It is possible that by increasing the functionality of the resin or the hardener one may be able to further increase the resistance to radiation, since the system will be more crosslinked (rigid) than those containing diepoxide only. Polyepoxide resins, derived from phenol formaldehyde condensation products of novolac structure and epichlorhydrin, have been prepared. The functionality of the hardener may be increased in aromatic amino compounds by using either compounds such as 4, 4', 4''-triamino triphenyl methane which have relatively high melting points and are soluble only with difficulty in epoxide resins, or an aniline formaldehyde condensation product. The latter has been prepared by Bishop in a suitable form. He produced a low-melting-point solid which was compatible with epoxide resin, producing a cured system with a heat-distortion point comparable with that of aromatic amine systems⁽¹⁶³⁾

Colichman and Strong⁽¹⁶⁴⁾ have also shown that the curing system and the reactive diluent used have a large effect on the radiation stability of epoxy resins. The best radiation resistance is obtained with aromatic-type curing agents such as m-phenylenediamine and pyromellitic dianhydride. Data obtained by Colichman and Strong show that epoxy plastics of high heat-distortion temperatures are more resistant to radiation than those having lower-temperature resistance. Pyromellitic dianhydride curing systems produce epoxy plastics having high heat-distortion temperatures (500 to 575 F). When such a system received the maximum radiation dose used, 10^{10} ergs g^{-1} (C), the heat-distortion temperature decreased from 575 F to approximately 550 F.

Epon 828 with diethylaminopropylamine as the catalyst maintained its properties up to 9.5×10^{10} ergs g^{-1} (C).⁽⁷⁰⁾ On the other hand, Epon 1001 with dicyandiamide as the catalyst did not show good stability. This was attributed to the hardener used.

Keller⁽⁹⁾ tested a heat-resistant epoxy and a regular epoxy laminate to determine the dose for threshold damage at room temperature. Both laminates contained glass fiber as the reinforcing agent. The heat-resistant epoxy laminate was the least resistant of the two, showing some degradation after an exposure dose of 8.3×10^{10} ergs g^{-1} (C) and considerable degradation after an exposure dose of 2.5×10^{11} ergs g^{-1} (C). The regular epoxy laminate reached a radiation threshold damage somewhat beyond 2.5×10^{11} ergs g^{-1} (C), and significant loss of strength did not occur until 8.3×10^{11} ergs g^{-1} (C). (See Table 19.)

In addition to room-temperature studies, the heat-resistant epoxy laminate was irradiated at 500 F for 200 hours to a total exposure dose of 8.3×10^9 ergs g^{-1} (C).

Compressive strength dropped considerably when the laminates were subjected to heat alone. However, the effect of heat and radiation was not as severe as that of heat alone.

Scintillators have been investigated as a means of improving the radiation resistance of epoxy resins. These materials absorb nuclear radiation and emit the energy in the form of visible radiation which does not damage the material. Stanford Research Institute found that one of these compounds, diphenyloxazole, improved the radiation resistance of Epon VIII. (165) Lap-shear specimens containing 9.1 per cent of the diphenyloxazole lost only 11 per cent of their strength when subjected to a beta-radiation dosage of 8×10^{10} ergs g^{-1} (C). Control specimens under the same conditions lost 40 per cent of their strength.

On the basis of limited studies, epoxy-phenolic resins have very good radiation stability, maintaining their properties up to a dose of 10^{11} ergs g^{-1} (C). One epoxy-adhesive, Epon 422 J, was irradiated at 77 to 68 F (25 to 30 C) to a dose of approximately 6.8×10^9 ergs g^{-1} (C). Even when tested at 500 F, it showed only about 25 per cent loss of tensile-shear strength. (10) The combined effect of heat and radiation has not been determined at the present time.

Hunter (166), in his study of plastic shields for reducing permanent nuclear-radiation damage, found that epoxy resins can be used to advantage to decrease the amount of permanent damage to sensitive transistors, or other solid-state devices. However, large quantities of plastic would be needed to completely eliminate this damage, and the effects of the thermalization of fast neutrons -- an increase in the number of thermal neutrons and an increase in the number of gamma rays present -- on transient effects in the devices have not been considered. It is expected that some interesting data on transient effects would be obtained from an experiment in which operating devices were surrounded by large quantities of plastic and exposed to the Godiva reactor. If, as a result of such experiments, it was learned that thermal neutrons were a contributor to the transient damage, it would be quite simple to add small amounts of thermal-neutron shield material to the over-all shield, and thereby remove the thermal -- with subsequent increase in gamma field, however.

Mixer (32) prepared model compounds of diglycidyl ether of Bisphenol A (DEBA), Epon 1001, and Epon X-131 by reacting them with n-propyl alcohol, phenol, n-butylamine, diethylamine, and aniline. The compounds thus represent segments of the cured polymer chain between crosslinks and, in some cases (with amines), they represent the segment including the crosslinking amino groups.

The chemical damage resulting from irradiation appears to be a cleavage of the amine groups, which volatilize, and a crosslinking of the polymer moieties. The order of stability of resins appears to be Epon X-131 > Epon 1001 > Epon 828, and that of the stability of the crosslinking agents $\text{NH}_2 > \text{Et}_2\text{NH} \sim \text{BuNH}_2$. A comparison of damage to model compounds and to adhesives at the same dose range shows that a small amount of chemical damage can result in large changes in physical properties in the cured adhesive. In view of the similar constitution (resinwise) of glass laminates, it is apparent that the high glass-filler content (65 to 70 per cent) in the laminates exerts a tremendous protective effect.

Isocyanate resins. Isocyanate resins, commonly known as polyurethanes, are formed by the reaction of compounds containing two or more active hydrogen groups, such as hydroxyl, amino, or carboxyl groups, with diisocyanates. The principal

compounds used at the present time are polyesters and polyethers. Linear polyesters reacted with diisocyanates usually give elastic polyurethanes, while highly branched polyesters give rigid polyurethanes.

Flexible and rigid polyurethane foams are becoming increasingly important because of their high tensile strength, excellent tear and abrasion resistance, chemical resistance, dielectric properties, and low thermal conductivity. They can be used up to 150 C, depending on the composition. Because of their dielectric properties, they are used as radome and antenna housings in aircraft.

Tomashot⁽⁷⁰⁾ tested the ultimate flexural strength and flatwise compressive strength of polyurethane foam sandwich constructions after irradiation. The foam sandwich sample showed no reduction in mechanical properties up to 1×10^{11} ergs g⁻¹ (C), the largest dose to which the samples were subjected.

Polyester Resins. Unfilled polyesters have poor radiation stability, hardening and developing small cracks under irradiation. Although the stability of various polyesters will vary somewhat, their properties begin to change at approximately 10^7 to 10^8 ergs g⁻¹ (C). Tensile strength and impact strength decrease, although tensile strength may increase at first.

Golichman and Scarborough at Atomic International studied the radiation stability of unfilled polyesters.⁽¹⁶⁷⁾ The materials tested are listed in Table 67. They found that Selectron 5003 improved up to 20 per cent in tensile strength and Young's modulus. The other materials were not significantly changed. No changes in hardness or heat-distortion properties at doses of 9.09×10^7 to 4.5×10^9 ergs g⁻¹ (C) (1.0×10^6 to 5.0×10^7 rads) were noted. Styrene-modified polyester syrups can be completely cured by irradiation at these doses, but properties of the cured products are not significantly superior to those cured by conventional methods.

TABLE 67. DESCRIPTION OF POLYESTER RESINS TESTED⁽¹⁶⁷⁾

Polyester Resin	Approximate Composition	Applications
Selectron 5003(a)	Unsaturated alkyd, styrene modified	General purpose
Selectron 5016(a)	Unsaturated alkyd, styrene modified	General purpose
Laminac 4123(b)	Unsaturated alkyd (maleic anhydride and/or ethylene glycol), styrene modified	General purpose
Laminac 4128(b)	Unsaturated alkyd (maleic anhydride and propylene and/or ethylene glycol), styrene modified (35 per cent styrene)	Formulated for retention of strength at elevated temperatures; aircraft accessories, storage tanks, etc.
Laminac 4202(b)	Unsaturated alkyd same as above but containing 30 per cent of diallyl phthalate instead of styrene	High-viscosity resin; good for hand lay-up, high-temperature application, radomes, etc.

(a) Pittsburgh Plate Glass Co.

(b) American Cyanamid Co.

Charlesby and co-workers⁽¹⁶⁸⁾ also studied the effects of nuclear radiation on the curing of polyester syrups. Following are the polyesters used in these studies:

Polyester	Components	Molecular Weight	Double Bonds per Molecule
A	Diethylene glycol, maleic acid	2166	11.6
B	Diethylene glycol, maleic acid	783	1.6
C	Propylene glycol, maleic acid, succinic acid	768	2.9
D	Propylene glycol, maleic acid, succinic acid	721	4.3
E	Ethylene glycol, propylene glycol, adipic acid	1860	0.0

The first effect noted was the increase in viscosity. Incipient gelation occurred, and further irradiation caused the gel to become rigid. The extent of conversion was found to be dependent only on the total dose and not on the intensity of radiation. The effect of various additives on the dose required to produce gelation is shown in Table 68, and their effect on time of gel is shown in Table 69.

Oriented films appear to have greater stability than the random polymer. Mylar (polyethylene terephthalate), a polyester film, has been reported stable up to 10^{11} ergs g^{-1} , absorbed dose (10^9 rads), when subjected to electron radiation.⁽⁵⁶⁾ On the other hand, Harrington indicates that Mylar reaches threshold damage at an exposure dose of 4.4×10^8 ergs g^{-1} (C) (5×10^6 roentgens) and 25 per cent damage at about 8.7×10^9 ergs g^{-1} (C) (10^8 roentgens).

Irradiation in vacuum to 8.7×10^9 ergs g^{-1} (C) produced the same damage as 4.4×10^9 ergs g^{-1} (C) in air, indicating that oxidation plays some part in the damage induced. Mylar is unaffected during thermal aging up to 200 C (392 F) by irradiation, except at levels above 10^{10} ergs g^{-1} (C).

Dacron is a fiber having the same chemical composition as Mylar polyester film. Because of its radiation stability, it has been recommended for use as tire cords where radiation stability is essential. Dacron is not adversely affected by air when irradiated, as shown by tensile and elongation strengths and the flex life of Dacron tire cords when irradiated in air and in a vacuum (see Table 31).

Upon exposure to a radiation dose of 4.56×10^{11} ergs g^{-1} (C) (1.5×10^{18} n cm^{-2}), polyethylene terephthalate (Dacron) fibers begin to powder with complete loss of strength.⁽¹⁶⁹⁾ Crystallinity does not change, which gives evidence that irradiation does not induce crosslinking. Rather, the effect of radiation on polyethylene terephthalate is to induce chain cleavage.⁽¹⁶¹⁾

In a study to determine the comparative stability of various fibers used for tire cords, Dacron with quinhydrone or quinone used as antirads showed better resistance to radiation than the other tire-cord fibers examined.⁽¹⁰⁹⁾ Dacron, both with and without the antirad, showed the best retention of stress-strain properties after irradiation.

Allyl diglycol carbonate, used as a casting resin or adhesive for optical glass, is one of the more radiation-resistant polyesters. It is unaffected by radiation to 1.5×10^8 ergs g^{-1} (C) and is damaged by 25 per cent at a dosage of 8.8×10^9 ergs g^{-1} (C). Elongation of this material increases to a maximum of more than 250 per cent at a dose of 5.5×10^{10} ergs g^{-1} (C) and then decreases rapidly.

TABLE 68. EFFECT OF ADDITIVES ON DOSE REQUIRED TO PRODUCE GELATION⁽¹⁶⁸⁾

Additive	Concentration, ppm	Exposure Dose, ergs g ⁻¹ (C)	Gelation Dose, megarads	Increase in EV Required per Molecule of Additive
None	--	5.1×10^7	0.56	--
Anthracene	1000	1.0×10^8	1.10	9:9
8-Hydroxy quinoline	1000	7.2×10^7	0.80	3:5
Nitrobenzene	2000	7.2×10^7	0.79	1:4
Allyl thiourea	1000	6.5×10^7	0.72	1:8
Naphthalene	1000	5.1×10^7	0.56	--
Diphenylolpropane	1000	5.1×10^7	0.56	--
Alpha-naphthylamine	1000	5.1×10^7	0.56	--
Beta-naphthylamine	1000	5.1×10^7	0.56	--
Phenol	1000	5.1×10^7	0.56	--
Benzoquinone	300	9.1×10^7	1.00	16:4
	600	1.14×10^8	1.26	13:4
	1000	2.04×10^8	2.24	16:6
	2000	3.5×10^8	3.82	18:3

TABLE 69. EFFECT OF ADDITIVES ON TIME TO GEL⁽¹⁶⁸⁾

Initiator 1 Per Cent Benzoyl Peroxide at 90 C

Additive	Concentration, ppm	Time to Gel, min
None	--	51.5
Quinone	300	98.5
Anthracene	1000	65.5
Naphthalene	1000	51.5
8-Hydroxy quinoline	1000	77

An environmental control system containing a silicone-impregnated Dacron⁽¹⁰⁷⁾ diaphragm in the control valves exhibited no failure at 5×10^9 ergs g^{-1} (C).

The addition of mineral fillers increases the radiation stability of polyesters by approximately 100-fold. Bopp and Sisman⁽⁷⁶⁾ found that the physical properties of Plaskon Alkyd, a mineral-filled polyester, began to deteriorate at a radiation dose of 8.6×10^9 ergs g^{-1} (C), as compared to 10^7 or 10^8 ergs g^{-1} (C) for unfilled polyesters. Deterioration by 25 per cent was attained at a dose of 3.9×10^{11} ergs g^{-1} (C), after which properties decreased rapidly.

Polyester laminates show good radiation stability. Johnson and Sicilio⁽⁸⁰⁾ irradiated several types of glass fiber-polyester laminates used in aircraft construction to a total exposure dose of approximately 2.4×10^9 ergs g^{-1} (C) (6×10^{14} fast $n\text{-cm}^{-2}$, 6×10^{13} (nv₀)t, and 5×10^{16} gamma photons/ cm^2). No major changes in the physical properties of the laminates were found after this exposure.

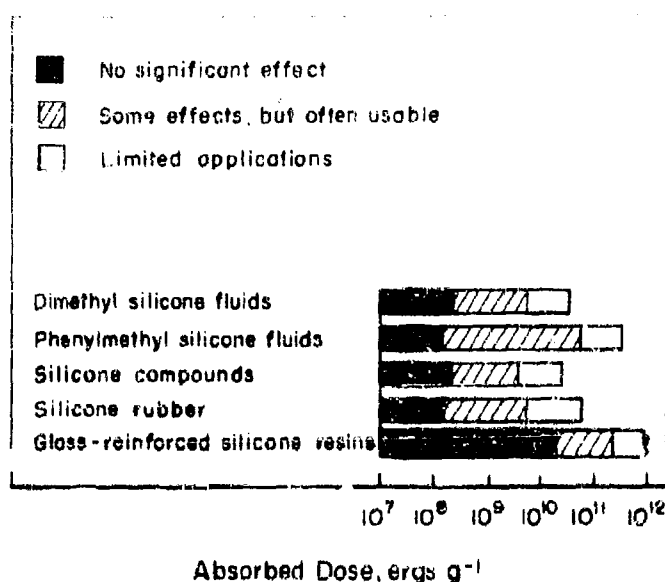
Keller⁽⁹⁾, in an effort to determine threshold damage for laminates, irradiated a polyester and a heat-resistant (TAC) polyester to 8.3×10^{11} ergs g^{-1} (C). When irradiated at room temperature, the TAC polyester reaching threshold damage between 8.3×10^{10} and 2.49×10^{11} ergs g^{-1} (C) was less resistant to radiation than the regularly cured polyester which reached threshold damage between 2.49×10^{11} and 8.3×10^{11} ergs g^{-1} (C) (see Table 17). These laminates were not irradiated at elevated temperatures.

Silicone Resins. Silicone resins, used for laminates, coatings, and insulating materials, are not seriously degraded at exposure doses to 10^9 or 10^{10} ergs g^{-1} (C) and, with the proper filler, are satisfactory to 10^{11} ergs g^{-1} (C). Dielectric properties are only slightly lowered at the latter exposure.

The stability of aliphatic polysiloxanes to radiation is below that of polystyrene and polyethylene and similar to that of the polyamides.⁽⁶⁷⁾ The presence of phenyl groups in the silicone chain increases radiation stability, while the presence of methyl groups increases flexibility. Silicone resins generally have a high phenyl content and are reasonably good with respect to radiation resistance. Silicone fluids are less resistant to radiation than the resins. Again, the presence of the phenyl group improves the radiation resistance of the fluid. Phenylmethyl silicone fluids and methyl-hydrogen silicone fluids are more radiation resistant than the dimethyl silicone fluids.⁽⁷⁹⁾ Figure 15 shows the radiation stability of several types of silicone compounds.

Silicone polymers initially crosslink when irradiated. As a confirmation of the resistance of phenyl-containing silicone high polymers to radiation crosslinking, it may be noted that a phenylmethylpolysiloxane subjected to 1.86×10^{10} ergs g^{-1} (C) was crosslinked to about the same extent as a dimethylpolysiloxane at a dose of 10^9 ergs g^{-1} (C) (146)

Glass laminates fabricated with silicone resins show exceptionally good radiation resistance. They reach a threshold of degradation when exposed to gamma-radiation doses to 10^{11} ergs g^{-1} (C).⁽⁹⁾ Phenolic resin laminates modified with silicones show even better resistance to radiation.



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FIGURE 15. RADIATION RESISTANCE OF SILICONES(50)

Keller⁽⁹⁾ determined the threshold of degradation caused by gamma radiation for silicone-glass fiber reinforced laminates and studied the combined effects of heat and radiation on these laminates. At room temperature, silicone laminates reach threshold damage at about 10^{11} ergs g^{-1} (C). However, tensile strength does not drop off until 2.49×10^{11} ergs g^{-1} (C).

The combination of heat and radiation was no more detrimental than heat alone to these laminates, except at the highest exposure dose [8.3×10^9 ergs g^{-1} (C)]. (See Table 19.) Laminates exposed to 4.2×10^9 ergs g^{-1} (C) at 500 F had a flexural strength only about 15 per cent less than that of laminates exposed to 500 F with no irradiation. However, flexural strength of the laminates exposed to heat alone decreased to approximately 42 per cent of the original value.

A silicone-glass cloth laminate exposed to a gamma flux of 1.3×10^{11} photons $cm^{-2} sec^{-1}$ for a period of 3 months suffered neither color nor dimensional changes. Assuming an average photon energy of 1 Mev, this is a dose of about 5×10^{10} ergs g^{-1} (C). However, its insulation resistance jumped from 10^2 to 9×10^3 megohms. (47)

Asbestos-silicone laminates have been tested at room temperature and have shown no apparent change in properties to an absorbed dose of 1.1 to 2.0×10^{10} ergs g^{-1} (1.1 to 2.0×10^8 rads). (77) At 6×10^{10} ergs g^{-1} (6×10^8 rads), tensile strength increased 10 per cent, shear strength decreased 5 per cent, hardness increased 5 per cent, and specific gravity increased 5 per cent, while the gas evolved amounted to 7 ml/g.

A new extreme-temperature silicone encapsulant, still in the development stage, is reported to have good radiation resistance (specific data are not given). (170) The material, designated as Dow Corning R-7521 resin, is a solventless silicone resin compounded with an inorganic filler. Owing to its excellent radiation resistance, this material is believed to be suitable for use in motors, controls, and other devices designed

for use with nuclear reactors. Radiation-resistance studies have shown this filled resin to be essentially unaffected, both physically and electrically, by doses as high as 1.8×10^{11} ergs g^{-1} (C) (2,000 megarads). Similar radiation resistance is expected of zirconium orthosilicate-filled silicone resin.

Although little, if any, difficulty with this new material is expected for most commercial applications, the extreme thermal-shock requirements of specifications may limit its use in airborne and ordnance equipment.

For most applications, irradiation up to 9.1×10^{10} ergs g^{-1} (C) (1,000 megarads) has no appreciable effect on the major properties of the silica-filled R-7521 resin. However, several effects were noted. The color was slightly darkened, and rapid-rise electric strength was increased by irradiation from 4.5×10^{10} to 9.1×10^{10} ergs g^{-1} (C) (500 to 1,000 megarads), low-frequency dissipation factor was increased slightly, dielectric constant was increased very slightly, moisture resistance was decreased on the surface, arc-resistance measurements became more consistent and were low in value, and dielectric losses during irradiation were large and were a strong function of the dose rate.

Dow Corning 301 molding compound was irradiated at the Nuclear Aircraft Research Facility at Convair at ambient temperature. (17) Table 70 shows that tensile strength apparently increased at all flux levels, compressive strength showed no appreciable change, and water absorption doubled at the highest dose.

TABLE 70. EFFECTS OF RADIATION ON DOW CORNING 301 MOLDING COMPOUND (17)

Group	Flux		Tensile Strength, lb	Compressive Strength, psi	Water Absorption After 24-Hour Immersion, per cent
	Gamma, ergs g^{-1} (C)	Neutron, n cm^{-2}			
Controls			1196	10,700	0.113
I	5.5×10^7	9.9×10^{12}			0.101
II	5.5×10^8	9.9×10^{13}			0.129
III	5.5×10^9	9.9×10^{14}			0.231
IV	6.0×10^7	4.3×10^{12}	1408	10,900	
V	2.8×10^8	2.6×10^{13}	1670	10,400	
VI	2.8×10^9	2.6×10^{14}	1323	11,300	
VII(a)	2.8×10^8	2.6×10^{13}	1571		
VIII(a)	2.8×10^8	2.6×10^{13}	1309		

(a) All groups were irradiated at ambient temperature with the exception of Group VII and Group VIII which were irradiated at -65 F and 400 F, respectively.

Furane Resins. Furane resins, consisting of furfural-phenol and furfuryl alcohol-dimethylol types, are heat- and corrosion-resistant thermosetting plastics. These resins are brittle, however, and their applications are usually limited to special molding compounds, adhesives, and coatings.

The only studies so far noted on these resins are those of Bopp and Sisman. (5) They report that Duralon (urane with asbestos and carbon-black filler, manufactured by the U. S. Stoneware Company) changed very little in properties up to a radiation exposure of over 10^{11} ergs g^{-1} (C).

Amino Resins. Amino resins (urea formaldehyde, melamine formaldehyde, and aniline formaldehyde) are thermosetting resins used in shockproof laminates, wiring devices, adhesives, and surface coating formulations. Because of their electrical-insulation properties, they are used in electronic equipment and in aircraft ignition parts.

Urea formaldehyde resins are, in general, about average for plastics in radiation resistance. Such plastics are unaffected by radiation doses up to 8.3×10^8 ergs g^{-1} (C) and are damaged by 25 per cent at a dose of 5.1×10^9 ergs g^{-1} (C).

Melamine formaldehyde plastics are slightly more radiation resistant than are the urea formaldehyde types, being unaffected up to a dose of 7.4×10^8 ergs g^{-1} (C) and damaged by 25 per cent at a dose of 1.1×10^{10} ergs g^{-1} (C). Urea- and melamine-formaldehyde resins, when filled with cellulosic materials, become brittle, blister, swell, and crumble upon exposure to gamma radiation. (5)

Polyaniline formaldehyde, a linear polymer which is generally thermoplastic, has better resistance to radiation than the above two types of plastics in all properties except impact strength. The impact strength of this plastic is unaffected at 7.4×10^7 ergs g^{-1} (C) and damaged by 25 per cent at a dose of 1.4×10^9 ergs g^{-1} (C). Because of its poor stability with respect to impact strength, polyaniline formaldehyde is rated below urea formaldehyde in radiation stability. For applications where impact strength is not important, it would be considered as having excellent radiation stability. However, use of polyaniline formaldehyde is limited because of its poor heat resistance.

Thermoplastic Resins

Styrene Polymers and Copolymers. From the standpoint of change in physical properties and hydrogen evolution during irradiation, polystyrene is one of the most stable of all high polymers. This stability is believed due to the dissipation of the radiation energy of the benzene-ring structure.

Polystyrene exhibits threshold degradation at 10^{10} ergs g^{-1} (C) and 25 per cent damage at greater than 4×10^{11} ergs g^{-1} (C). Infrared spectra reveal that exposure doses of 10^{12} ergs g^{-1} (C) are required in a vacuum to produce significant spectral change. (68) An exposure dose of 10^{12} ergs g^{-1} (10^{10} rads) appears to start a wholesale disruption of the polystyrene molecule.

Oxidation plays little or no part in the radiation damage of polystyrene. However, there is a postirradiation oxidation effect which continues for at least 23 days. (171) It is believed that this is due, in part, to the formation of free radicals during irradiation. There are indications that this oxygen comes from molecular oxygen in air and not from water vapor. (80) This is shown by the fact that polystyrene absorbing 3.5×10^{11} ergs g^{-1} (3.5×10^9 rads) in the Oak Ridge graphite reactor showed far greater OH and C=O bond intensities after exposure to an atmosphere of oxygen for 14 days than after

exposure to saturated water vapor for the same length of time. Also, the OII absorption in polystyrene receiving an absorbed dose of 10^{13} ergs g^{-1} (10^{11} rads) was not lessened by the sample remaining in a vacuum of 0.2 micron for 4 days.

Parkinson and Binder also studied the postirradiation oxidative effects on polystyrene. Samples which had received doses of 1.8×10^{11} ergs g^{-1} (C) (2×10^9 rads) or more oxidized to hydroxyl and carbonyl products on exposure to air. (172) The rate of oxidation appeared to be dependent on the dose. The molecular weight of irradiated polystyrene stored at room temperature in a vacuum did not change appreciably for periods up to 200 hours if the radiation dose was below that required for gelation. Charlesby reported that gelation begins at the equivalent of 1.5×10^{10} ergs g^{-1} (C) (a slow-neutron flux of 0.5×10^{17} n cm^{-2}) (173).

Polystyrene retains its optical properties better than Plexiglas or glass under ionizing radiations. (174)

The radiation stability of styrene copolymers is generally poorer than that of the styrene polymer itself. For example, SBR (GR-S), a copolymer of styrene and butadiene is less resistant to radiation than polystyrene. Also, a high-impact-strength polystyrene, when irradiated, lost its impact strength rapidly until it was no better than the unmodified polystyrene, showing that the modifying agent was affected rather than the polystyrene.

Irradiation of poly-alpha-methylstyrene was carried out by the Naval Research Laboratory. Their results show the chain scission and growth of unsaturation occurs (see Table A-86). (175) A later study (176) indicated that the unsaturation did not reside in the polymer molecule itself but that it took place in the low-molecular-weight component (1000 or less), which could be extracted from the polymer in a benzene solution.

Radiation-induced polymerization of alpha-methylstyrene was examined by Hirota and co-workers at the University of Osaka. (177) They learned that, at doses of 5.3×10^8 ergs g^{-1} (C) (6×10^6 roentgens), carbon tetrachloride additives accelerated the polymerization, naphthalene retarded it, and ortho- and parabenzquinone inhibited it almost completely.

Polyvinyl Carbazole. Polyvinyl carbazole is one of the more radiation-resistant nonfilled plastics. It has a threshold-damage dose of 8.8×10^9 ergs g^{-1} (C) and is damaged by 25 per cent at about 4.4×10^{11} ergs g^{-1} (C). (113) It is somewhat affected by a radiation dose lower than that for polystyrene, but both are damaged by 25 per cent at about the same dose. However, the carbazole resin is brittle and its applications are, therefore, limited.

Polyvinyl Chloride. Polyvinyl chloride (PVC) is equivalent to polyethylene in its radiation stability. Its properties begin to change at a radiation dose of 1.9×10^9 ergs g^{-1} (C), while it is damaged by 25 per cent at a dose of 1.1×10^{10} ergs g^{-1} (C). Tensile strength of PVC is not affected until it is given a radiation dose higher than that which affects polyethylene. However, the tensile strength of polyethylene first increases and then decreases. PVC decreases more rapidly than polyethylene in tensile strength, but its elongation does not decrease as rapidly as that of polyethylene.

Harrington and Giberson⁽²⁰⁾ report that no HCl was found in mass-spectrometer analyses of polyvinyl chloride. This material was irradiated to 5×10^8 ergs g⁻¹ (C). Bopp and Sisman⁽⁷⁶⁾ reported HCl as one of the irradiation products, although perhaps the HCl was evolved at higher dosages. The liberation of hydrogen chloride when PVC is irradiated makes this material unsuitable for many applications in a nuclear environment.

A polyvinyl chloride compound, Geon 2046, was found to be stable to nuclear radiation to an absorbed dose of 1.9×10^9 ergs g⁻¹, and changed by 25 per cent at 1.1×10^{10} ergs g⁻¹.⁽⁶⁹⁾ Harrington and Giberson⁽²⁰⁾ report two additional Geon compounds, 3630 and 8640, to have somewhat lower radiation stability. These compounds show a radiation-sensitive threshold at an exposure dose of less than 4.4×10^8 ergs g⁻¹ (C) (5×10^6 roentgens) and 25 per cent damage at approximately 4.4×10^9 ergs g⁻¹ (C) (5×10^7 roentgens). These variations may be due primarily to sample thickness. The material reported in REIC Report No. 3⁽⁶⁹⁾ was 80 mil, while the materials reported by Harrington and Giberson⁽²⁰⁾ were 4 and 20 mil. Table 71* lists the changes in elongation and tensile strength found by Harrington and Giberson.

TABLE 71. CHANGE IN PHYSICAL PROPERTIES OF POLYVINYL CHLORIDE DUE TO IRRADIATION⁽²⁰⁾

	Exposure Dose		Elongation		Tensile Strength	
	ergs g ⁻¹ (C)	roentgen $\times 10^{-11}$	Per Cent	%	Psi	%
Geon 8630 (0.004 in.)	0	0	245		2555	
	4.4×10^8	5		-10.7		-25.6
	8.7×10^8	10		-21.3		-34.5
	4.4×10^9	50		-29.5		-30.2
	8.7×10^9	100		-35.8		-31.6
Geon 8630 (0.020 in.)	0	0	300		2730	
	4.4×10^8	5		4.0		-5.7
	8.7×10^8	10		4.0		-0.2
	4.4×10^9	50		-13.2		-10.2
	8.7×10^9	100		-23.3		-0.3
Geon 8640 (0.004 in.)	0	0	225		3140	
	4.4×10^8	5		-8.5		-13.3
	8.7×10^8	10		-11.8		-20.1
	4.4×10^9	50		-34.4		-41.4
	8.7×10^9	100		-46.7		-42.3
		100-V(a)		-50.1		-22.4
Geon 8640 (0.020 in.)	0	0	325		3580	
	4.4×10^8	5		-5.3		-5.1
	8.7×10^8	10		-5.2		-4.1
	4.4×10^9	50		-22.5		-32.0
	8.7×10^9	100		-32.5		-31.2

(a) Irradiated in vacuum.

The breaking strength, breaking elongation, viscosity, and thermal shrinkage for samples of polyvinyl chloride subjected to gamma irradiation in vacuum at 0 to 2.6×10^9 ergs g⁻¹ (C) (0 to 3×10^7 roentgens) were studied by Takayanagi and co-workers at Kyushu University⁽¹⁷⁸⁾. They found that the breaking strength decreased with increasing radiation. Breaking elongations were not affected. The degree of polymerization estimated from viscosity measurements decreased with irradiation at lower

* Table 71 is a duplicate of Table 16. It is repeated here for the reader's convenience in making a comparison with the text.

doses, while it showed a tendency to rise at higher doses again. The irradiation effects on thermal shrinkage became markedly visible only at higher temperatures.

Studies of the coloration of three types of polyvinyl chloride films irradiated at 8.8×10^7 to 2.6×10^9 ergs g^{-1} (C) (10^6 to 3×10^7 roentgens) in air showed that the pure film gradually darkened at room temperature⁽¹⁷⁹⁾. The rate of coloration increased at higher temperatures. In films containing stabilizers, the noted color change was greater than for those with no stabilizer. Film containing a plasticizer had an absorption spectrum similar to that measured for the other two specimens, but in this case, the absorption did not reach a limiting value by heat treatment.

Data on the mechanism of radiation degradation of polyvinyl chloride are contradictory. McFedries of Dow Chemical reported that polymers containing halogens, such as polyvinyl chloride, tend to degrade⁽¹⁸⁰⁾, while Miller of General Electric reported that crosslinking occurs, resulting in a flexible, vulcanized product with no noticeable decomposition or loss in heat-aging characteristics⁽¹⁸¹⁾. Miller used Geon 101, containing Flexol DOP, dibasic lead phthalate (Dythal) stabilizer, polyethylenglycol dimethacrylate (monomer MG-1) additive, and Vulcan-9 filler. Doses ranged from approximately 8.7×10^6 to 1.8×10^9 ergs g^{-1} (C) (0.1 to 20 megareoentgens). No specific data were given in the McFedries report. An explanation for this apparent conflict in data may be found in the work of Wippler of Cie Saint Gobain, Antony, France, who reported that irradiation of pure polyvinyl chloride powder with a cobalt-60 source resulted in the occurrence of both degradation and crosslinking.⁽¹⁸²⁾ The presence or absence of air appears to determine to a great extent which mechanism is predominant.

Sakurada and co-workers at Osaka Laboratories attempted graft copolymerization of styrene to polyvinyl alcohol induced by gamma radiation.⁽¹⁸³⁾ Graft copolymers were obtained with polyvinyl alcohol films containing more than 5 per cent absorbed water, when they were suspended in styrene and with dry films of the alcohol suspended in a mixture of styrene, acetone, and water. Only homopolymers resulted when dry films of polyvinyl alcohol were suspended in styrene alone. Polyvinyl alcohol, which belongs to the so-called degradation-type polymer, can be crosslinked when irradiated in the presence of water.⁽¹⁸⁴⁾ Saito of Chuo University, Tokyo, states that the actual result is endlinking instead of crosslinking.⁽¹⁸⁵⁾

Polyethylene. Polyethylene is unaffected by radiation to absorbed dose of 1.9×10^9 ergs g^{-1} and accrues 25 per cent damage at 9.3×10^9 ergs g^{-1} .⁽⁵⁾ Tensile strength increases at first, but at approximately 1.1×10^{10} ergs g^{-1} (C), it begins to decrease and is 25 per cent lower than the initial value at approximately 10^{12} ergs g^{-1} (C).

Harrington and Gibson⁽²⁰⁾ observed a somewhat lower threshold value for polyethylene when they irradiated 3, 5, 10, and 15-mil films of polyethylene. No major differences in the radiation resistance of these films were noted. All showed a considerable change in properties between 4.4×10^8 ergs g^{-1} (C) (5×10^6 roentgens) and 8.7×10^8 ergs g^{-1} (C) (10^7 roentgens). The 15-mil films showed a greater increase in tensile strength at lower doses than did the thinner films.

Polyethylene is subject to oxidation when irradiated. This is one reason that thin films are degraded at lower radiation doses than thicker films. However, polyethylene shows very little postirradiation oxidation.⁽⁶⁸⁾ Samples irradiated by cobalt-60 to an exposure dose of 6.2×10^8 ergs g^{-1} (C) did not undergo oxidation after irradiation.

The softening point of polyethylene increases on irradiation with doses below 10^9 ergs g^{-1} (C). Meikle and Graham⁽¹⁸⁶⁾ produced a higher melting-point material by subjecting a standard grade of polyethylene to an electron-beam generator. The irradiated material operated as wire and cable insulation continuously at 150 C, for extended periods at 200 C, and for a few hours at 300 C. However, Charlesby⁽¹⁸⁷⁾ pointed out that, at higher radiation doses, polyethylene becomes a flexible, rubberlike material and, with continued radiation, it becomes a crosslinked material which is somewhat brittle and cheesy.

Harrington⁽¹⁸⁸⁾ tested several commercial polyethylenes, some containing carbon black, for radiation stability. Those materials containing carbon black and an antioxidant apparently had slightly better radiation stability than the standard polyethylene with respect to tensile strength but not with respect to elongation.

High-density polyethylene is much more crystalline than the low-density type, and, therefore, its radiation stability may be expected to be different. Harrington and Giberson⁽²⁰⁾ state that a high-density polyethylene (Marlex) is very susceptible to radiation damage and deteriorates at low exposures. The crosslinking ability of Marlex is greatly reduced, as shown by the decrease in tensile strength at low exposure doses. Marlex is about 95 per cent crystalline and has a density of 0.960. A 2-mil film was extremely brittle and crumbly after 4.4×10^9 ergs g^{-1} (C) (5×10^7 roentgens). Even at 4.4×10^8 ergs g^{-1} (C) (5×10^6 roentgens), elongation had decreased by 92 per cent and tensile strength had decreased by 12 per cent. However, in thicker films, Marlex behaves more like the lower density polyethylene. Table 15 shows the change in elongation and tensile strength with increasing radiation exposure for low- and high-density polyethylene.

A high-density material, Super Dylan, increased in tensile strength, decreased in elongation, and became brittle with exposure doses up to 7.8×10^9 ergs g^{-1} (C). On the basis of these data, it appears that the high-density material is slightly more resistant than the standard polyethylene, but not to the extent that it would be more serviceable.

The U. S. Rubber Company Research Center has attempted the incorporation of grafted polymers and metals into polyethylene in an effort to improve high-temperature properties⁽¹⁸⁹⁾. Experiments have been made to establish methods of grafting and to gain insight into the properties of the resulting polymers for establishing more definite routes of investigation. The most promising route found, to date, has been to incorporate fillers into the polymers, followed by grafting and curing either by radiation or chemical means. Radiation of samples containing oxides definitely shows some interaction between the filler and the polyethylene. Values of zero-strength temperature as high as 350 C (660 F) have been reached, indicating some degree of stability in the vicinity of this temperature. Zero-strength temperature is the temperature at which the material loses all tensile strength and is thus an approximate measurement of the melting point. Samples of the polyethylene containing metal oxides were also irradiated and subsequently grafted with a mixture of styrene and methacrylic acid. These grafted polymers gave a higher zero-strength temperature (660 F) than did the ungrafted.

Polyvinyl Formal. Polyvinyl formal, used as an adhesive and in wire and cable applications, is similar to polyvinyl butyral in its properties and applications. However, its radiation resistance is better than that of the butyral, and slightly poorer than that of PVC. Its threshold-damage dose is 1.6×10^9 ergs g^{-1} (C), and 25 per cent damage occurs at a dose of 1.2×10^{10} ergs g^{-1} (C). (76, 113)

Polyvinylidene Chloride. The radiation stability of polyvinylidene chloride (Saran) is between that of polyvinyl formal and polyvinyl butyral. It is approximately equal to that of urea formaldehyde and is about average for plastics. The threshold damage dose is 4.1×10^8 ergs g^{-1} (C), and 25 per cent damage occurs at 4.5×10^9 ergs g^{-1} (C). Saran softens, blackens, evolves hydrogen chloride, and decreases in tensile strength when irradiated. (190)

Polycarbonate. Polycarbonate resin is a light-amber, transparent thermoplastic-type molding resin which has high impact strength, excellent dimensional stability, good electrical properties, and good heat resistance. It can be used continuously at temperatures up to 275 F and for short-time operation to 285 or 300 F. The commercial resins have the structural unit $[-\text{OC}_6\text{H}_4\text{C}(\text{CH}_3)_2\text{C}_6\text{H}_4\text{OCO}-]$ and are the first commercially useful thermoplastic materials which incorporate the carbonate unit as an integral part of the main polymer chains. They are presently being used for coil forms, gears, cams, bushings, bearings, housing for business machines, and electrical apparatus. Other possibilities include lenses and instrument windows.

Harrington and Giberson⁽²⁰⁾ irradiated polycarbonate films (Lexan and Macrofol). The results were discussed previously in the section on films.

Fluoroethylene Polymers. Fluoroethylene polymers, tetrafluoroethylene (Teflon), and monochlorotrifluoroethylene (Kel-F, fluorothene, polyfluoron, and others) are widely used in seals, gaskets, and electrical equipment where high temperature and corrosion resistance are the requirements. These types of plastics are readily susceptible to radiation damage. The presence of chlorine in Kel-F, with its large capture cross section, makes it particularly susceptible to damage by slow neutrons. (191) Fluorinated materials do not crosslink, but, instead, the fluorine atom is liberated and reacts to break a carbon-to-carbon bond, which contributes to the poor resistance of fluoroethylene polymers to radiation.

Generally, the radiation chemistry of fluorocarbons can be related to the changes observed in the physical and mechanical properties of the irradiated polymer. (192) The rapid degradation of polytetrafluoroethylene by ionizing radiation can be attributed chiefly to the prevalence of main chain scission by liberated fluorine atoms and the production of entrapped fluorocarbon gases.

Possibilities for improving the radiation resistance of fluorocarbon polymers include developing styrene-type structures and incorporating fluorine-atom scavengers in the molecule, e. g., hydrogen or trifluoromethyl radicals.

Collins and Calkins⁽¹¹³⁾ reported threshold damage for Teflon as 1.7×10^6 ergs g^{-1} and 25 per cent damage as 3.4×10^6 ergs g^{-1} (3.7×10^4 rads).

According to Harrington⁽¹⁸⁸⁾ tensile strength of Teflon decreases by 40 per cent after a dosage of 3×10^8 ergs g^{-1} (C), while the elongation decreases by 93 per cent; Teflon becomes very brittle and crumbly.

Teflon has been irradiated under various environmental conditions at Inland Testing Laboratories⁽¹⁷⁾. It has been irradiated at -65 F, 73 F, and 350 F to a total gamma exposure of 2.6×10^7 ergs g^{-1} (C). Exposure was made in atmospheres of air and

nitrogen. The conclusion reached was that the initial decrease in tensile strength was a function of the irradiation and testing temperature. For irradiations and tests at both 73 and 350 F, the tensile strength decreased to between 40 and 60 per cent of the original values at the exposure dose, 2.6×10^7 ergs g^{-1} (C). At -65 F, the effect of irradiation was negligible at the same radiation exposure. Elongation also depended on the irradiation dose and the test temperature. At 350 F, elongation was 15 to 20 per cent of the control values. At 73 F, it was 40 to 60 per cent of the control values. Teflon irradiated in nitrogen at 350 F maintained a higher tensile strength and elongation than when irradiated in air at the same temperature. This increase in stability was not noted at 73 F.

Measurements of several dielectric properties of Teflon were made before, during, and after gamma irradiation by Loy of The Martin Company at Baltimore. (193) Post-irradiation measurements of the dielectric constant of specimens ranging in thickness from 3 to 125-mil showed no significant change after irradiation to a dose of 5.0×10^9 ergs g^{-1} (C) (5.7×10^7 roentgens). The volume resistivity of specimens irradiated at dose rates ranging from 2.6×10^4 to 1.6×10^7 ergs g^{-1} (C) hr^{-1} (3×10^2 roentgens hr^{-1} to 1.85×10^5 roentgens hr^{-1}) decreased very rapidly during irradiation. After approximately 20 hours, resistivity reached a constant value which was a factor of 10^3 below the preirradiation value. It increased after removal from the irradiation field. Results indicate that resistivity varies inversely with dose rate and specimen thickness. Postirradiation values of resistivity are dependent on the dose which the specimen received.

General Electric Company (101) has found that Teflon, when immersed in a jet turbine oil [MIL-7808 (a sebacate ester)], shows improved stability to radiation. Table 72 shows the property changes of this material when irradiated in air, and in jet turbine oil at 400 F.

TABLE 72. PROPERTY CHANGES IN A FLUORINATED POLYMER
IRRADIATED IN AIR, ARGON, AND JET TURBINE
OIL AT 400 F BY COBALT-60 (101)

Material(a)	Environment	Radiation Dose, ergs g^{-1} (C)	Physical Properties		
			Tensile Strength, psi	Elongation, per cent	Hardness, Shore
	Air	0	2435	234	97.5
"	Air	4.4×10^7	1342	0	97.6
"	Air	4.4×10^8	616	0	97.8
"	MIL-L-7808 Oil(c)	8.7×10^6	1471	33	97.2
"	MIL-L-7808 Oil(c)	8.7×10^7	1534	4.6	97.8
"	MIL-L-7808 Oil(c)	8.7×10^8	834	0	98.8

(a) Samples were tensile dumbbells.

(b) Teflon is a trademark for Du Pont polytetrafluoroethylene.

(c) MIL-L-7808 Oil is a synthetic diester jet turbine oil.

Tests to determine the suitability of Teflon for flexible connector applications were made by Cooke at General Electric. (194) A Teflon tube was enclosed in a stainless steel wire-braid sheath and exposed to doses of 8.8×10^6 to 2.6×10^7 ergs g^{-1} (C) (1 to 3×10^5 roentgens). In the tests Fluoroflex Teflon was found to be both stronger and more flexible than the ordinary white variety. After exposure to 8.8×10^7 ergs g^{-1} (C) (10^6 roentgens), the tensile strength was approximately equal to that of the unirradiated white material. Failure of the connector was due to stress corrosion of the stainless steel braid caused in part by adsorption of HF, from the Teflon, on the outer surface of the steel thimble where the Teflon had been tightly pressed into the corrugations to give a hermetic seal.

Kel-F which was not plasticized, was subjected to 6×10^{14} fast n cm^{-2} , 6×10^{13} (nv₀)t, and 5×10^{16} gamma photons cm^{-2} . (80) This exposure represents a total exposure dose of approximately 2.4×10^9 ergs g^{-1} (C). At this exposure dose, the ultimate tensile strength of Kel-F was not changed. Elongation increased 47 per cent, and impact strength decreased 16 per cent. Table 73 gives the values before and after irradiation. These compare with the radiation stability of Kel-F as reported by Bopp and Sisman and as given in REIC Report No. 3⁽⁶⁹⁾ in which threshold damage is reported as 1.3×10^8 ergs g^{-1} and 25 per cent damage is given as 2×10^9 ergs g^{-1} .

TABLE 73. EFFECT OF RADIATION ON PHYSICAL PROPERTIES OF UNPLASTICIZED KEL-F⁽⁸⁰⁾

Property	Control Sample, Not Irradiated	Sample Irradiated to 4.0×10^9 Ergs G^{-1} (C)
Ultimate Tensile Strength, psi	5022	5022
Elongation, per cent	46.8	67.2
Impact Strength, in-lb/in. width	21.3	17.9
Water Absorption	0.00	0.048
Specific Gravity at 26 C	2.12	2.11
Surface Resistivity, ohms	17.8×10^6	17.8×10^6
Volume Resistivity, ohms/in.	2.5×10^{11}	2.5×10^6

Radiation Applications, Inc., has reported that radiation grafting can make fluorocarbon polymers such as Teflon and Kel-F bondable and dyeable with water-soluble dyes⁽¹⁹⁵⁾. Wetting properties of the polymer surface can be adjusted by the treatment. The material is not given enough radiation to seriously affect its properties, and the company is presently able to form a product which is completely stable up to 250 C. (196) It is reported that the tensile strength of a typical treated Teflon tape increased from 2300 to about 3000 psi after treatment. Elongation of the same piece of tape decreased from 200 to about 120 per cent. These values can be varied by controlling treatment conditions and the physical properties of the original tape.

Two polyvinyl fluoride resins, R-20 and R-22 film materials, tested by Harrington, were found to possess some strength and resisted breaking when subjected to the bend test after exposure to 4.4×10^9 ergs g^{-1} (C) (5×10^8 roentgens). (127) R-22 showed slightly more resistance to radiation.

Polyvinyl Butyral. Polyvinyl butyral is unaffected by radiation to a dose of 4.7×10^8 ergs g^{-1} (C) and is damaged by 25 per cent at a dose of 1.9×10^9 ergs g^{-1} (C) which is below the average of polymeric materials. Tensile strength decreases rapidly

after 10^9 ergs g^{-1} (C). Upon irradiation, the material first softens and then becomes more brittle. (76) Polyvinyl butyral is used as an interliner for safety glass in automobiles and aircraft.

Cellulosics. Cellulosic polymers, such as cellulose acetate, cellulose acetate butyrate, cellulose nitrate, cellulose propionate, and ethyl cellulose are among the polymers least resistant to radiation damage. The physical properties of the cellulosics deteriorate rapidly under gamma radiation. At doses of 1.9×10^9 ergs g^{-1} (C), cellulose acetate, one of the more radiation-resistant cellulosics, has deteriorated by 25 per cent.

In the case of cellulose acetate, irradiation does not appear to affect the breakdown voltage. The lack of change in the dielectric properties is unexpected, since the mechanical properties are extremely sensitive to radiation. (197)

Acrylics. Polymethyl methacrylate (Lucite or Plexiglas), a transparent thermoplastic material having a softening point of 150 to 210 F, is below the average of most plastics in radiation stability. Its stability is about equal to that of styrene butadiene (SBR) rubber. It is unaffected by radiation to 8.2×10^7 ergs g^{-1} (C), but tensile strength and elongation are decreased at a dosage of 1.1×10^9 ergs g^{-1} (C). The physical properties deteriorate quite rapidly above that amount of radiation. Above 10^9 ergs g^{-1} (C) of absorbed radiation, polymethyl methacrylate becomes very brittle.

Light transmittance drops from 91 to 56 per cent at 5.5×10^8 ergs g^{-1} (C) of absorbed radiation, (198) although there is only a slight increase in haze. At a controlled temperature of 77 F, Plexiglas 55 turns from colorless to dark yellow with increased absorption of gamma radiation (cobalt-60). At higher radiation doses, polymethyl methacrylate is reported to have turned brown.

Postirradiation oxidation and molecular-weight changes in polymethyl methacrylate were studied by Parkinson and Binder at Oak Ridge. (172) They found that the polymer, irradiated to doses of 7.3×10^7 to 1.3×10^8 ergs g^{-1} (C) (0.8 and 1.4×10^6 rads), showed postirradiation decreases in molecular weight after 500 hours of about 0.2×10^{18} scissions per gram. Heating the irradiated polymethyl methacrylate to 80 C for 1 to 6 hours produced approximately the same number of scissions as storage at room temperature for 500 hours. After the material was heated to 80 C, a slow increase in molecular weight was observed. Shultz and co-workers proved that air retards the radiation-induced main-chain scissions of this polymer. (199)

When polymethyl methacrylate deteriorates under radiation, the main polymer chains are ruptured, and the side chains are decomposed, giving gaseous products. These gaseous decomposition products can expand the material five to ten times its original volume. (190)

Polymethyl alphachloroacrylate (Grafite) has been examined for radiation resistance and, in general, its physical properties and radiation resistance were found to be no better than those of polymethyl methacrylate. (198) This material has a higher heat-distortion temperature than polymethyl methacrylate and is, therefore, considered for use in aircraft canopies, windows, and dial covers.

Graft copolymerization in the polyethylacrylate-acrylonitrile system was carried out at Osaka University using gamma irradiation from a 13-curie cobalt-60 source. (200) Indications were that the main chains were broken by irradiation at the same type polymerization took place and that both block-type and graft-type polymers coexisted in the products.

Polyamides. Nylon, tested in sheet form, reaches threshold damage at an absorbed dose of 8.6×10^7 ergs g^{-1} and 25 per cent damage at 4.7×10^8 ergs g^{-1} . Its tensile strength increases with radiation, reaching 25 per cent increase at 10^{11} ergs g^{-1} (C). (69) In contrast to this, the oriented polymer, nylon fiber, does not show an increase in tensile strength. At a dose of 8.5×10^8 ergs g^{-1} (C) nylon fiber irradiated in air was reported to have lost more than 50 per cent of its original strength. (121) A possible explanation of this behavior may be attributed to the differences in the crystallinity of nylon fiber and nylon sheet. Another explanation may be the effect of oxygen on nylon.

Although tensile strength of nylon increases by 25 per cent at a dose of over 10^{11} ergs g^{-1} (C), elongation decreases very rapidly, having changed by 25 per cent at approximately 5×10^8 ergs g^{-1} (C). Impact strength decreases at approximately the same ratio as elongation.

The crosslinking of nylon when irradiated is not proportional to the dose. (201) Crosslinking for 6-6 nylon seems to saturate at about 10 per cent, indicating that chain scission plays an important role.

Little (169) found that nylon, on irradiation in the Clinton reactor operating at full power, evolved gaseous hydrogen at a rate which decreased as the dose increased, and low-molecular-weight compounds were formed which could be extracted.

Little (169) also found that nylon fiber rapidly loses strength when irradiated in the presence of air. However, the service life of nylon in air can be increased by the use of antirads or antioxidants. According to Born (109), both quinone and pyrogallol give a fourfold extension in service life of nylon, based on the retention of stress-strain properties. Nylon with an age resistor and phenothiazine were practically as strong after exposure to 1.7×10^9 ergs g^{-1} (C) as nylon cord was before irradiation. (69) The irradiated cord had an ultimate elongation 1.5 times as great. However, it should be noted that tests conducted by Goodrich indicate that Dacron would probably be superior to nylon as a tire cord used in a radiation environment.

The strength and fracture of drawn and undrawn nylon were studied by Hsiao and co-workers at the University of Minnesota. (202) From tensile studies the ultimate strength of the undrawn nylon decreases markedly to a minimum after a thermal-neutron bombardment of 6.36×10^3 ergs g^{-1} (C) (6×10^{10} nvt) as compared with that of the drawn nylon. However, at somewhat higher levels, the ultimate tensile strength of undrawn nylon increases while that of drawn nylon continues to decrease until they approach nearly the same level. Both materials show a sharp drop when a dose of 10^{12} ergs g^{-1} (C) (10^{19} nvt) is reached. Nylon used in this experiment was "Tynex" 610 filament.

Two nylons, an experimental polyamide (Polymer A) and Nylon 6, an Allied Perlen Type 30 (Polymer B), were studied by Smith at the Goodrich Research Laboratory to determine their tenacity loss. (51) Table A-87 shows the ratio of tenacity at a given

radiation exposure to the initial tenacity. Pure Polymer A has excellent stability against gamma-radiation-induced tenacity loss; however, the addition of all additives resulted in inferior fibers. Pure Polymer B was not stable to radiation, but several additives resulted in fibers with improved radiation resistance. The antirads used with these polymers are listed in Table A-88.

A new sheet insulation made by coating woven glass fabrics with a high-molecular-weight polyamide-type resin identified as MK polymer has been developed by Du Pont's Newburgh Research Laboratory. (203) Radiation effects on the material were investigated by exposing thin samples at a dose rate of about $90.9 \text{ ergs g}^{-1} (\text{C}) \text{ sec}^{-1}$ (1 megarad per second). Tests were conducted both at room temperature and at 200 C. The results of these tests are shown in Figures 16 and 17. These graphs represent permanent radiation effects.

Polyvinyl Chloride-Acetate. Polyvinyl chloride-acetate behaves similarly to Saran when irradiated. The damage threshold is reached at $1.4 \times 10^8 \text{ ergs g}^{-1} (\text{C})$, and 25 per cent damage occurs at $2.8 \times 10^8 \text{ ergs g}^{-1} (\text{C})$. It turns black after a very short period of irradiation. It softens even before showing any appreciable darkening, and elongation increases will be over 500 per cent before a dose of $5 \times 10^8 \text{ ergs g}^{-1}$ has been reached. (190)

Polyformaldehyde. Delrin acetal resin, a polyformaldehyde, was found to have extremely poor radiation stability, even at the relatively low dose of $4.4 \times 10^8 \text{ ergs g}^{-1} (\text{C})$ ($5 \times 10^6 \text{ roentgens}$). (127) Harrington suspects that degradation is due to chain cleavage.

Polypropylene. Polypropylene is chemically similar to polyethylene in that it is an aliphatic hydrocarbon polymer. It differs from polyethylene in that every other carbon atom has a methyl group attached. For this reason the polymer will not crystallize unless the segments of the chain form a repetitive geometric pattern. Such a pattern exists in the so-called "isotactic" polymer.

Polypropylene has been examined for radiation stability and found to be inferior to polyethylene. At an exposure dose where polyethylene has degraded by 25 per cent, polypropylene has become useless. Even at room temperature and a low relative humidity, it is too brittle after irradiation for use as electrical insulation. (61) At an exposure dose of $8.7 \times 10^9 \text{ ergs g}^{-1} (\text{C})$, it has become brittle and lost all of its elongation and most of its tensile strength. (62) Between 2.6×10^{10} and $8.7 \times 10^{10} \text{ ergs g}^{-1} (\text{C})$, it becomes increasingly softer and more flexible. It has been suggested that, at the high exposure dose, some of the polypropylene chains have become low in molecular weight due to chain cleavage and that the low-molecular-weight material plasticized the remainder of the polymer.

Electron crosslinking of polypropylene and high-density polyethylene was studied by F. G. Waddington (204), who noted no significant variation in G-value with density of polyethylene (see Table 74) after a dose of $9.09 \times 10^9 \text{ ergs g}^{-1} (\text{C})$ (100 megarads). He did observe, however, an indication that crosslinking proceeds slightly more efficiently at higher densities. The crosslinking efficiencies between Polypropylene A and B show a marked difference. The structure of polypropylene B is not known but that of A is believed to be mainly an isotactic form.

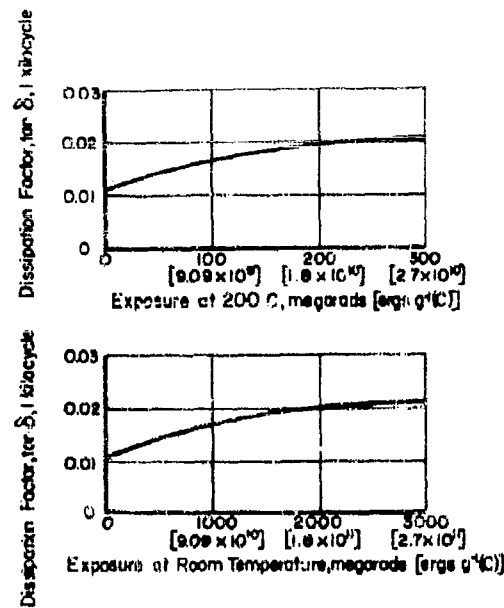


FIGURE 16. DISSIPATION FACTOR OF MK POLYAMIDE-COATED GLASS FABRIC VERSUS RADIATION EXPOSURE AT ROOM TEMPERATURE AND AT 200 C (203)

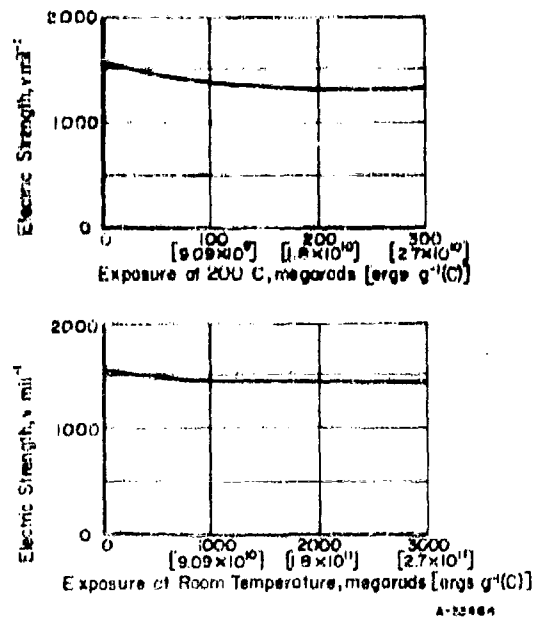


FIGURE 17. ELECTRIC STRENGTH VERSUS RADIATION DOSE FOR MK POLYAMIDE-COATED GLASS FABRIC (203)

TABLE 74. VARIATION IN G-VALUE WITH DENSITY OF POLYETHYLENE⁽²⁰⁴⁾

Material	Density, g cm ⁻³	G-Values	
		From Swelling Data	From Elasticity Data
Alkathene G2	0.93	2.4	2.3
Alkathene H. D.	0.94	2.3	2.3
Hostalen H. D.	0.96	2.7	2.4
Marlex 50	0.97	2.4	2.4
Polypropylene A	0.90	1.3	0.9
Polypropylene B	0.90	0.7	0.6

Epstein⁽²⁰⁵⁾ irradiated commercially available polypropylene and determined its mechanical and electrical properties after irradiation. These are shown in Table 75 and 76, respectively. Up to 1.76×10^9 ergs g⁻¹ (C) (17.6 megarads) there is a slight increase in stiffness, some loss in impact strength, and considerable reduction in ductility. Since the latter is rarely an important factor in applications, it is reasonable to recommend polypropylene for radiation exposures up to 10^9 ergs g⁻¹ (C) (10^7 rads). Beyond this, the material becomes weak and brittle. The crazing observed at 5.3×10^9 ergs g⁻¹ (C) (52.8 megarads) is probably due, not to density changes which are very slight, but rather to thermal stresses from the molding process and the general weakening irradiation.

TABLE 75. MECHANICAL PROPERTIES OF IRRADIATED POLYPROPYLENE

Dose, ergs g ⁻¹ (C)	Mrads	Tensile Strength, psi	Elongation, per cent	Flexural Strength			Impact Strength, ft-lb/in.
				Mod-0.5 inch	Max psi	Max Deflection, inch	
0	0	4540	>500	4450	4830	0.83	0.700
5.86×10^8	5.86	4420	300	4530	4620	0.71	0.634
1.76×10^9	17.6	4400	<10	4680	5150	0.87	0.361
5.3×10^9	52.8(a)	1740	<5	Failed	390	0.025	0.101

(a) Samples visibly crazed.

TABLE 76. ELECTRICAL PROPERTIES OF IRRADIATED POLYPROPYLENE

Dose, ergs g ⁻¹ (C)	Mrads	Electrical Strength, volts mil ⁻¹	Dielectric Constant			Power Factor		
			100 C	10 Kc	1 Megacycle	100 C	10 Kc	1 Megacycles
0	0	488	2.30	2.30	2.29	.0020	.0020	.0014
5.86×10^8	5.86	508	2.31	2.30	2.29	.0014	.0020	.0014
1.76×10^9	17.6	480	2.31	2.30	2.29	.0019	.0017	.0014
5.3×10^9	52.8(a)	434	2.30	2.30	2.29	.0019	.0013	.0014

(a) Samples visibly crazed.

It is significant that the early dose range, in which there appears to be a sharp drop in molecular weight, does not correspond to a sharp drop in mechanical properties. This supports the view that the mechanical properties are not strongly dependent on the molecular weight but rather on the molecular linearity and the attendant crystallinity. Accordingly, it does not appear feasible to improve the radiation resistance of polypropylene significantly by elimination of the "radiation weak links" which were suggested by analysis of viscosity data.

From the results of the electrical tests it is clear that the electrical properties are unaffected by any of the radiation dosages to which they were subjected, and that the material is limited in its application by mechanical damage.

Polypropylene, subjected to increasing gamma irradiation of the order of 10^9 to 3.5×10^{10} ergs g^{-1} (C), softened instead of progressively hardening with the increase in radiation dosage. (135) Grace and co-workers at Burke Research Company in Michigan noted that the inclusion of carbon black or a diene partially overcame the softening effect.

Harrington exposed a sample of propylene to 1.9×10^9 ergs g^{-1} (C) (2.2×10^7 roentgens) and found that it underwent severe damage. (127) It became brittle, lost all of its elongation, was discolored, and lost a significant amount of its tensile strength. The surface of the material became quite oily at the higher dose of 8.8×10^{10} ergs g^{-1} (C) (1×10^9 roentgens).

EFFECT OF RADIATION ON SPECIFIC PHYSICAL PROPERTIES OF PLASTICS

It is possible that a plastic will be satisfactory for a given application even though the material has deteriorated in "nonessential" physical properties. Therefore, to determine which plastic will give the best radiation resistance for a particular application, it is necessary to know the doses of radiation which will change the various properties of the polymers. The effects of radiation on tensile strength, elongation, elastic modulus, shear strength, and impact strength of plastics are compared for various materials in the following sections. The radiation doses necessary for threshold, 25 per cent, and 50 per cent change are shown in Figures D-1 through D-5 in Appendix D.

It must be remembered, however, that these results do not take into consideration methods which may be used to improve the radiation resistance of polymers, such as the addition of mineral fillers, antirads, or scintillators. The various tests used to determine these properties are primarily static-type tests carried out after irradiation, whereas the materials will be used under dynamic conditions in many cases. Also, these radiation studies have not taken into consideration other environmental conditions which, when combined with a radiation environment, may considerably alter the usefulness of the material being studied. Therefore, materials chosen for a specific purpose will have to be tested further under simulated or actual operating conditions.

Tensile Strength

Plastics showing the greatest stability with respect to tensile strength are polystyrene, asbestos-filled phenolics, furane resin, and polyvinyl carbazole. They show

practically no change to 10^{12} ergs g^{-1} (C). Nylon and graphite-filled phenolics show an increase in tensile strength. Polyethylene, after first increasing in tensile strength, shows a decrease of 25 per cent at 10^{12} ergs g^{-1} (C). Nylon, mineral-filled polyester, aniline formaldehyde, and polyvinyl chloride are changed by less than 25 per cent in tensile strength at 10^{11} ergs g^{-1} (C). An epoxy-glass fabric (Epon 828 resin) showed good stability, but was not tested beyond 10^{11} ergs g^{-1} (C). (10)

Elongation

Rigid plastics have very low initial elongations, in most cases amounting to less than 2 per cent. Irradiation has little effect on this property of most rigid plastics. Those plastics which do not appreciably change at 10^{11} ergs g^{-1} (C) include furane resin, aniline formaldehyde, phenolic resin with asbestos and with asbestos-fabric laminate, polyester with mineral filler, polystyrene, polystyrene with white pigment filler, and polyvinyl carbazole.

Of those plastics having an initial elongation of over 200 per cent, polyvinyl chloride was the most stable to radiation. Elongation is unaffected to 10^9 ergs g^{-1} (C) and decreases by 25 per cent at a dose of 10^{10} ergs g^{-1} (C). Teflon is the plastic most susceptible to damage with respect to elongation.

Elastic Modulus

Plastic materials showing the greatest radiation stability with respect to elastic modulus include aniline formaldehyde, melamine formaldehyde with cellulose filler, polyethylene, furane resin, phenolic resin with asbestos fiber or asbestos fabric, phenolic resin with graphite filler, polyester with mineral filler, polystyrene, polystyrene with black or white pigment filler, and polyvinyl carbazole. Polyethylene and polystyrene with black pigment filler have increasing elastic modulus values, while melamine formaldehyde and mineral-filled polyester have decreasing values. The other materials, furane resin, phenolic resin with asbestos fiber or fabric, phenolic resin with asbestos, polystyrene, polystyrene with white pigment filler, and polyvinyl carbazole do not change in value after having received almost 10^{12} ergs g^{-1} (C).

Shear Strength

Polymers having the least change in shear strength when irradiated include aniline formaldehyde, phenolic resin with asbestos fiber or graphite, nylon, mineral-filled polyester, allyl diglycol carbonate, polystyrene, polystyrene with black or white pigment filler, and polyvinyl carbazole. Phenolic resin filled with graphite and polystyrene increase in shear strength. The shear strength of nylon increases initially but decreases with increased doses of radiation. Aniline formaldehyde, mineral-filled polyester, and allyl diglycol carbonate decrease in shear strength. The shear strength of asbestos-fiber-filled phenolic resin, black and white pigmented polystyrene, and polyvinyl carbazole does change appreciably with doses of almost 10^{12} ergs g^{-1} (C).

Impact Strength

Melamine formaldehyde with cellulose filler, furane resin, phenolic resin with asbestos or graphite filler, mineral-filled polyesters, allyl diglycol carbonate, polystyrene, polystyrene with white pigment filler, polyvinyl carbazole, and vinyl chloride-acetate show good radiation stability with respect to impact strength. Melamine formaldehyde, mineral-filled polyester, and allyl diglycol carbonate decrease in impact strength, while the others do not change. Vinyl chloride-acetate does not change in impact strength to 4.4×10^{11} ergs g^{-1} (C), the maximum dose to which it was exposed, although it is one of the polymers whose over-all radiation stability is poor.

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RWK/NJB/SP:nb

APPENDIX A

RADIATION DAMAGE TABLES

TABLE A-1. COMPOSITION OF SOVIET CABLE RUBBERS (25)

Type of Vulcanizate	Raw Rubber Content, per cent	Raw Rubber	Filler	Softener	Antioxidant	Vulcanizing Agent	Activator
TSSh-30	30	Natural + sodium-polybutadiene (1:1)	Ground whitening	--	Phenyl- β -naphthylamine + mercapto-benzothiazole	Tetramethylthiuram disulfide	Zinc oxide
TSSh-35	35	Natural + sodium-polybutadiene (1:1)	Talc + whitening	Stearic acid + paraffin	Phenyl- β -naphthylamine	Ditto	Ditto
TS-35	35	Natural + sodium-polybutadiene (1:1)	Ditto	Ditto	Ditto	--	--
NSH-35	35	Polychloroprene + natural (7:1)	Whitening + kauri	Stearic acid + paraffin + kauri softener	--	Zinc oxide + magnesium oxide	--
SN-40	40	Polychloroprene	Whitening + lamp black	Stearic acid + dibutyl-pentabrate + softener 99	--	Ditto	--
SBM-40	40	Buna S + luminopolymerized butadiene (1:1)	Lamp black + kauri	Stearic acid + pelleted bitumen + softener 99	--	Sulfur + mercapto-benzothiazole	Zinc oxide

TABLE A-2. AGING OF CABLE RUBBERS

Radiation Dose		TSSH-30			TSSH-35			TS-35		
Ergs G ⁻¹ (C)	Mr	σ , kg cm ⁻² (a)	ϵ , per cent	Q, per cent	σ , kg cm ⁻²	ϵ , per cent	Q, per cent	σ , kg cm ⁻²	ϵ , per cent	Q, per cent
0	0	61.0	679	44	73.1	753	47	73.9	588	43
1.9 x 10 ⁹	21.6	55.0	650	54	60.9	700	45	61.0	591	48
4.6 x 10 ⁹	53	40.5	610	57	44.2	538	45	51.0	537	51
1.1 x 10 ¹⁰	192	22.3	410	29	22.8	417	25	34.6	388	20
1.5 x 10 ¹⁰	170	23.4	227	13	22.9	302	15	32.0	270	18
1.9 x 10 ¹⁰	220	24.6	188	7	23.7	222	8	32.9	237	13
2.6 x 10 ¹⁰	300	20.4	144	4	34.6	103	3	36.2	173	9

(a) 1 kg cm⁻² = 14,223 psiNote: σ = tensile strength; ϵ = breaking elongation; Q = tension set.

TABLE A-3. VARIATION IN THE DIELECTRIC PROPERTIES OF

Rubber	Time Submerged in Water at 20 C, days	0				Radiation Dose, 2.0 x 10 ¹⁰		
		ρ , ohm-cm	$\tan \delta$	ϵ	E_b , kv mm ⁻¹ (a)	ρ , ohm-cm	$\tan \delta$	ϵ
TSSH-30	before submerison	8.4 x 10 ¹⁰	0.008	4.2	40.1	7.2 x 10 ¹⁴	--	4.4
TSSH-35	Ditto	7.0 x 10 ¹⁰	0.019	4.3	40.0	1.0 x 10 ¹⁵	--	4.0
TS-35	"	8.5 x 10 ¹⁰	0.010	4.3	51.0	2.0 x 10 ¹⁵	--	4.4
NSM-30	"	3.3 x 10 ¹²	0.073	8.3	31.5	1.3 x 10 ¹²	--	9.4
TSSH-30	1	1.0 x 10 ¹³	0.025	6.0	--	1.2 x 10 ¹²	0.221	7.8
TSSH-35	1	2.3 x 10 ¹⁰	0.050	4.0	--	7.1 x 10 ¹¹	0.162	6.8
TS-30	1	1.2 x 10 ¹⁰	0.081	5.4	--	2.8 x 10 ¹⁴	0.003	5.0
NSM-30	1	2.8 x 10 ¹²	0.085	9.0	--	0.6 x 10 ¹¹	0.171	11.0
TSSH-30	4	8.7 x 10 ¹¹	0.201	7.8	--	8.7 x 10 ¹¹	0.246	8.3
TSSH-35	4	1.4 x 10 ¹⁴	0.090	5.	--	1.8 x 10 ¹²	0.208	7.0
TS-35	4	1.35 x 10 ¹⁴	0.088	6.1	--	1.6 x 10 ¹⁴	0.097	6.0
NSM-30	4	3.7 x 10 ¹²	0.095	10.0	--	1.4 x 10 ¹²	--	11.0
TSSH-30	7	1.1 x 10 ¹²	0.192	7.6	--	3.6 x 10 ¹¹	0.140	9.1
TSSH-35	7	1.7 x 10 ¹³	0.114	6.1	--	3.7 x 10 ¹¹	0.303	9.6
TS-35	7	4.9 x 10 ¹³	0.097	6.1	--	4.3 x 10 ¹³	0.105	6.3
NSM-30	7	8.6 x 10 ¹²	0.103	10.7	--	1.4 x 10 ¹²	0.208	13.4
TSSH-30	14	5.6 x 10 ¹¹	0.282	8.3	8.5	2.3 x 10 ¹¹	0.550	10.9
TSSH-35	14	9.7 x 10 ¹¹	0.269	8.0	10.6	1.3 x 10 ¹¹	0.612	15.7
TS-35	14	1.0 x 10 ¹⁵	0.141	6.3	12.0	2.9 x 10 ¹³	0.121	6.6
NSM-35	14	2.3 x 10 ¹²	0.167	12.5	13.1	8.5 x 10 ¹¹	Could not be measured	

(a) kv mm⁻¹ x 0.0254 = volts mil⁻¹.Note: ρ = volume resistivity; $\tan \delta$ = tangent of the angle of dielectric losses; ϵ = dielectric permittivity; E_b = breakdown voltage.

SUBJECTED TO RADIATION FROM $\text{Cs}^{60(25)}$

NSH-35			ShN-40			ShBM-40		
σ , kg cm ⁻²	ϵ , per cent	Q, per cent	σ , kg cm ⁻²	ϵ , per cent	Q, per cent	σ , kg cm ⁻²	ϵ , per cent	Q, per cent
71.9	669	55	76.3	457	18	65.3	409	22
65.5	542	53	78.2	361	16	68.3	259	14
50.4	346	40	73.1	281	15	75.6	249	13
58.7	32	6	67.1	113	2	73.7	210	7
72.9	64	4	91.2	102	5	83.1	166	6
86.3	58	0	99.4	94	0	89.4	124	4
112.0	22	0	122.1	54	0	97.3	132	3

CABLE RUBBERS SUBJECTED TO RADIATION FROM $\text{Cs}^{60(25)}$

$\text{ergs cm}^{-2} (\text{C})$							
7.8×10^9				1.3×10^{10}			
ρ , ohm-cm	$\tan \delta$	ϵ	E , kv mm ⁻¹	ρ , ohm-cm	$\tan \delta$	ϵ	E , kv mm ⁻¹
2.0×10^{14}	0.010	4.1	34.7	3.9×10^{13}	0.024	4.4	30.0
2.3×10^{14}	0.023	4.1	50.0	2.5×10^{13}	0.066	4.8	35.4
3.2×10^{14}	0.024	4.3	40.0	7.2×10^{13}	0.062	4.7	44.3
2.0×10^{11}	0.041	11.5	16.5	1.8×10^{11}	0.168	14.4	0.68
2.0×10^{11}	0.188	0.8	18.4	5.8×10^{11}	0.167	0.3	25.7
1.2×10^{12}	0.160	0.1	20.0	7.0×10^{11}	0.193	6.8	30.0
4.6×10^{12}	0.140	0.6	20.7	2.0×10^{12}	0.167	7.2	20.8
2.9×10^{11}	0.101	12.7	14.2	1.0×10^{11}	0.211	10.2	7.9
1.0×10^{11}	0.243	8.1	--	1.6×10^{11}	0.203	7.0	--
1.4×10^{11}	0.236	8.0	--	5.8×10^{10}	0.310	9.7	--
1.8×10^{10}	0.236	8.4	--	1.0×10^{11}	0.256	9.1	--
1.8×10^{11}	0.310	9.0	--	1.4×10^{11}	0.343	10.6	--
5.8×10^{11}	0.603	0.5	--	5.3×10^{10}	0.282	8.6	--
9.6×10^{10}	0.523	9.3	--	2.4×10^{10}	0.465	12.4	--
6.6×10^{10}	0.338	9.6	--	3.2×10^{10}	0.491	11.4	--
3.1×10^{11}	0.809	10.8	--	2.1×10^{10}	0.608	33.3	--
3.5×10^{10}	0.562	10.5	--	3.3×10^{10}	Could not be measured Ditto "		
2.7×10^{10}	0.484	12.0	--	1.3×10^{10}			
2.1×10^{10}	0.671	14.0	--	1.4×10^{10}			
5.5×10^{10}	Could not be measured		--	8.0×10^8			

TABLE A-4. EFFECT OF 75 F IRRADIATION ON TENSILE-SHEAR STRENGTH, BEND STRENGTH, AND FATIGUE RESISTANCE OF ADHESIVE 422J (EPOXY-PHENOLIC) TESTED AT 75, 180, 260, AND 500 F(10)*

Tensile-Shear Strength							
Temperature, F	Radiation Dose		Shear Strength, psi	(s)	σ (psi)	σ (psi)	σ (psi)
	$\times 10^7$	$\text{MRg g}^{-1} (\text{C})$					
Room temperature	0	0	2380	49	0.02	55	0.02
	7.5	6.5×10^9	2270	78	0.04	87	0.04
	20	1.7×10^{10}	2280	55	0.02	67	0.03
	93.5	8.1×10^{10}	2150	95	0.04	106	0.05
180	7.5	6.5×10^9	2260	79	0.03	88	0.03
	20	1.7×10^{10}	2290	129	0.05	144	0.05
	93.5	8.1×10^{10}	2240	79	0.04	88	0.04
260	8	7×10^9	1900	76	0.04	85	0.04
	25	2.2×10^{10}	1900	59	0.01	56	0.01
	93.5	8.1×10^{10}	2050	72	0.03	80	0.04
500	6.8	5.9×10^9	1730	54	0.04	59	0.04
	25	2.2×10^{10}	1560	135	0.09	149	0.10
	93.5	8.1×10^{10}	1470	77	0.05	80	0.05
Bend Strength							
Temperature, F	Radiation Dose		Bend Strength, psi	(s)	σ (psi)	σ (psi)	σ (psi)
	$\times 10^7$	$\text{MRg g}^{-1} (\text{C})$					
Room temperature	0	0	126	4.4	0.03	4.9	0.04
	6.8	5.9×10^9	125	4.1	0.03	4.6	0.04
	25	2.2×10^{10}	120	10.1	0.08	11.1	0.08
	93	8.1×10^{10}	122	11.2	0.09	12.6	0.10
180	7.5	6.5×10^9	121	2.5	0.02	2.8	0.02
	25	2.2×10^{10}	119	5.6	0.05	5.4	0.05
	78	4.8×10^{10}	121	3.5	0.01	3.9	0.01
260	6.6	5.8×10^9	108	4.1	0.04	4.9	0.04
	25	2.2×10^{10}	111	8.7	0.08	9.8	0.09
	63	5.7×10^{10}	105	6.2	0.06	6.9	0.07
500	8	7×10^9	94	7.2	0.06	5.9	0.06
	25	2.2×10^{10}	89	7.0	0.04	4.0	0.04
	75.5	6.6×10^{10}	89	4.1	0.05	4.5	0.05
Fatigue Strength							
Temperature, F	Radiation Dose		Load psi	Cycles $\times 10^3$	Type of Failure		
	$\times 10^7$	$\text{MRg g}^{-1} (\text{C})$					
Room temperature	0	0	1625	5	Adhesive		
			1405	146	Adhesive		
			1765	224	Adhesive		
			1125	4,639	Adhesive		
			1125	15,000	None		
	7.5	7×10^9	1625	49	Adhesive		
			1405	373	Adhesive		
			1765	2,489	Adhesive		
			1125	1,195	Adhesive		
			1125	20,000	None		
	78	6.8×10^{10}	1405	4	Adhesive		
			1405	49	Adhesive		
			1765	505	Adhesive		
			1125	8,499	Adhesive		
			980	25,000	None		

Note: Testing conditions: 330 f and 50 cps for 30 minutes (11).

* References given on page 26.

(a) = standard deviation of the point, computed according to the equation $\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N}}$ where

x_i = strength test value of particular specimen

\bar{x} = arithmetic average of the five specimens undergoing a particular test

N = number of specimens in the group

(b) = stress strength ratio

(c) = standard deviation corrected to account for the effect of sample size on the estimate, calculated by means of the relation

(d) = bend strength, psi

TABLE A-5. EFFECT OF RADIATION ON STRENGTH PROPERTIES OF SANDWICH PANELS BONDED WITH HEXCEL 422J⁽³¹⁾

Type Test	Results Calculated as	Control (X_C)			Irradiated (X_I)			$(X_I - X_C) \pm P^{(a)}$	Interpretation
		Max.	Min.	Mean	Max.	Min.	Mean		
Aluminum Skin - Glass Core									
Core Compression	Face Compression, psi	1400	1103	1204	1447	1024	1220	-20 ± 60	No change
Simple Beam	Failing Load, psi	816	400	479	483	360	460	-14 ± 28	No change
Column Creep	Failing Time, hr	18.8	9.0	12.3	14.3	6.0	10.1	-2.2 ± 1.8	Decrease
Shear Modulus	G_C , 10^3 psi	49.6	24.0	32.4	48.6	23.0	35.9	1.6 ± 3.6	No change
Shear Stress	S_C , psi	609	478	585	594	398	520	-65 ± 30	Decrease
Aluminum Skin - Aluminum Core									
Core Compression	Face Compression, psi	321	201	262	327	257	295	1 ± 21	No change
Simple Beam	Failing Load, psi	380	280	329	353	278	310	-13 ± 28	No change
Column Creep	Failing Time, hr	11.7	6.0	8.7	12.4	0.1	10.2	-1.6 ± 2.1	No change
Shear Modulus	G_C , 10^3 psi	317.9	48.6	88.3	161.6	56.6	96.0	0.7 ± 2.1	Increase
Shear Stress	S_C , psi	305	274	283	328	200	268	-18 ± 17	No change

Note: Tested at 200 F.

Total doses 2.4×10^6 ergs g^{-1} (C) (6×10^{14} nrvt, 6×10^{13} nrvt, and 6×10^{10} gammas/ cm^2).

(a) P = precision at 95 per cent confidence interval.

TABLE A-6. EFFECT OF 75 F IRRADIATION ON TENSILE SHEAR STRENGTH, BOND STRENGTH, AND FATIGUE RESISTANCE OF ADHESIVE FM 47 (VINYL-PHENOLIC) TESTED AT 75, 180, AND 260 F (10)

Tensile Shear Strength							
Temperature, F	Radiation Dose		Shear Strength, psi	\bar{x} (1)	σ (2)	σ/\bar{x} (3)	
	$r \times 10^{-2}$	$\text{mr/g} \times 10^3$ (C)					
Room temperature	0	0	3400	233	0.06	262	0.07
	8.5	7.4×10^9	3920	136	0.03	152	0.04
	32	2.4×10^{10}	3740	267	0.02	298	0.06
	81	7.1×10^{10}	3480	190	0.11	435	0.12
180	8.5	7.4×10^9	3360	332	0.12	444	0.13
	32	2.8×10^{10}	2620	549	0.21	614	0.22
	99	8.6×10^{10}	2160	256	0.13	309	0.14
260	9.9	8.6×10^9	1470	17	0.04	64	0.04
	32	2.8×10^{10}	1190	75	0.08	106	0.09
	99	8.6×10^{10}	1190	98	0.08	110	0.09

Bond Strength							
Temperature, F	Radiation Dose		Bond Strength, lb	\bar{x} (1)	σ (2)	σ/\bar{x} (3)	
	$r \times 10^{-2}$	$\text{mr/g} \times 10^3$ (C)					
Room temperature	0	0	186	7.3	0.04	8.2	0.04
	9.9	8.6×10^9	184	16.7	0.09	18.7	0.10
	32	2.8×10^{10}	153	10.4	0.07	11.6	0.08
	99	8.6×10^{10}	155	9.6	0.06	10.7	0.07
180	9.9	8.6×10^9	227	9.7	0.04	10.3	0.05
	32	2.8×10^{10}	216	12.5	0.08	14.4	0.09
	99	8.6×10^{10}	191	4.5	0.07	4.9	0.07
260	9.9	8.6×10^9	181	6.7	0.04	7.5	0.04
	32	2.8×10^{10}	176	8.1	0.05	9.1	0.05
	99	8.6×10^{10}	145	10.1	0.07	11.6	0.08

Fatigue Strength						
Temperature, F	Radiation Dose		Load, psi	Cycles $\times 10^{-3}$	Type of Failure	
	$r \times 10^{-2}$	$\text{mr/g} \times 10^3$ (C)				
Room temperature	0	0	1600	96	Adhesive	
			1335	235	Adhesive	
			1065	675	Adhesive	
			880	2401	Adhesive	
			665	8045	Adhesive	
	9.9	8.6×10^9	1620	67	Adhesive	
			1335	130	Adhesive	
			1065	430	Adhesive	
			935	1067	Adhesive	
			800	2401	Adhesive	
	81	7.1×10^{10}	1335	211	Adhesive	
			1065	297	Adhesive	
			935	2817	Adhesive	
			860	10,000	None	
			800	20,000	None	

Note: (1) \bar{x} = 300 psi and 200 psi for 75 samples (13).(2) σ = standard deviation of the group, computed according to the equation

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n}}$$

where x_i = strength test value of particular specimen \bar{x} = arithmetic average of the five specimens undergoing a particular test n = number of specimens in the group(3) σ/\bar{x} = shear strength (psi)(4) σ = standard deviation entered in column for the weight of specimens in each group, divided by square of the modulus

$$\sigma = \frac{\sigma}{E}$$

(5) σ/\bar{x} = bond strength (psi)

TABLE A-7. EFFECT OF BETA AND GAMMA IRRADIATION ON TENSILE-SHEAR STRENGTH OF FM-47 ADHESIVE (32)

Adhesive	Radiation Source	Radiation Dose		Average Shear Strength, psi	$\bar{\sigma}$ (a), psi	$\bar{\sigma}/(\bar{\sigma})(b)$	Per Cent of Original	Failure, Estimated Per Cent Adhesive
		rep $\times 10^{-2}$	ergs g^{-1} (C)					
FM-47	Beta(c, d)	0	0	4250	31.6	0.0074	100	100
		10	9.4×10^8	4450	50.0	0.011	104.7	100
		31	2.6×10^9	4250	38.7	0.0092	98.8	100
		81	6.8×10^9	1800	50.2	0.037	38	100
	Gamma	0	0	3600	150	0.042	100	100
		8.5	7.2×10^8	3700	220	0.050	103	100
		31	6.0×10^9	1800	134	0.080	40	100

(a) $\bar{\sigma}$ = corrected standard deviation of the group, computed according to the equation:

$$\bar{\sigma} = \sqrt{\frac{\sum (x - \bar{x})^2}{N-1}},$$

where

x = strength test value of particular specimen

\bar{x} = arithmetical average of the five specimens undergoing a particular test

N = number of specimens in the group.

(b) $(\bar{\sigma})$ = average shear strength, psi.

(c) Lap-shear specimens from 20-mil 2024-13 aluminum bonded to 83 mil; irradiated through 20-mil strips 20-mil strips reinforced with 83- mil strips prior to breaking.

(d) 1/4-inch lap instead of normal 1/2-inch lap.

TABLE A-8. EFFECT OF 75 F IRRADIATION ON TENSILE-SHEAR STRENGTH, BEND STRENGTH, AND FATIGUE RESISTANCE OF CYCLOWELD 55-9 ADHESIVE (VINYL-PHENOLIC) TESTED AT 75, 180, AND 260 F (10)

Tensile-Shear Strength										
Temperature, F	Radiation Dose		Shear Strength, (13)				Adjusted Shear Strength (10)			
	$r \times 10^{-7}$	$\text{rads } g^{-1} (C)$	psi	ksi	σ (psi)	σ (ksi)	psi	ksi	σ (T/F)	σ (T/F)
Room temperature	0	0	5750	974	0.26	1089	0.29			
	9.3	2.2×10^9	3750	917	0.24	1020	0.27	4204	275	0.05
	28	2.4×10^{10}	1250	507	0.41	567	0.46	1450	298	0.21
	107.5	9.4×10^{10}	640	246	0.38	275	0.43			
180	10.1	8.8×10^9	1160	96	0.08	107	0.09			
	28	2.4×10^{10}	910	132	0.14	148	0.16			
	89	7.8×10^{10}	1240	189	0.15	211	0.22			
260	8.3	7.2×10^9	700	73	0.11	80	0.12			
	36	2.6×10^{10}	490	109	0.22	122	0.25			
	107.5	9.4×10^{10}	410	265	0.65	300	0.73			

Bend Strength										
Temperature, F	Radiation Dose		Bend Strength, (14)				Adjusted Bend Strength (10)			
	$r \times 10^{-7}$	$\text{rads } g^{-1} (C)$	lb	ksi	σ (lb)	σ (ksi)	lb	ksi	σ (D/R)	σ (D/R)
Room temperature	0	0	196	11.3	0.06	12.6	0.06			
	8.3	2.2×10^9	183	29.9	0.16	13.4	0.12			
	28	2.4×10^{10}	124	44.6	0.39	54.4	0.44			
	107.5	9.4×10^{10}	13	25.4	0.40	28.4	0.45			
180	10.1	8.8×10^9	105	27.3	0.23	10.5	0.29			
	30	2.6×10^{10}	94	33.0	0.33	14.8	0.37	115	9.3	0.06
	107.5	9.4×10^{10}	96	8.3	0.09	9.3	0.10			
260	10.1	8.8×10^9	84	20.2	0.24	22.6	0.27			
	30	2.6×10^{10}	44	9.2	0.14	10.3	0.16			
	107.5	9.4×10^{10}	30	6.0	0.06	4.5	0.11			

Fatigue Strength					
Temperature, F	Radiation Dose		Load, psi	Cycles $\times 10^{-3}$	Type of Failure
	$r \times 10^{-7}$	$\text{rads } g^{-1} (C)$			
Room temperature	0	0	1040	394	Adhesive
			1610	112	Adhesive
			1333	4	Adhesive
			1066	111	Adhesive
			800	10,000	None
89		7.8×10^{10}	620	Failed while loading	
			600	10,000	None
			666	1815	Adhesive
			800	3698	Adhesive
			1065	7	Adhesive

(10) σ = standard deviation of the group, computed according to the equation $\sigma = \sqrt{\sum (x_i - \bar{x})^2 / n}$

where x_i = strength test value of particular specimen

\bar{x} = arithmetical average of the five specimens undergoing a particular test

n = number of specimens in the group

(13) σ = shear strength, psi

(14) σ = standard deviation computed by equation for the standard deviation of specimens in each group, computed by means of the relation

$$\sigma = \sqrt{\sum (x_i - \bar{x})^2 / n}$$

(15) In cases where one of the five test values deviated excessively from the average, it was discarded. The adjusted strength is the average with the extreme value discarded.

(16) σ = adjusted shear strength, psi

(17) σ = bend strength, lb

(18) σ = adjusted bend strength, lb

TABLE A-9. EFFECT OF RADIATION^(a) ON TENSILE-SHEAR STRENGTH OF HEXCEL 422⁽³¹⁾

Temperature, F	Tensile-Shear Strength, psi						$(X_1 - X_0) \pm P^{(b)}$	Interpretation
	Control (X_0)			Irradiated (X_1)				
	Max.	Min.	Mean	Max.	Min.	Mean		
<u>2024-T3 Clad to 2024-T3 Clad Aluminum</u>								
Room temperature	2951	2513	2672	3051	2740	2895	253 \pm 695	No change
260	2494	2144	2323	2380	2280	2392	6 \pm 304	No change
<u>7075-T6 Unclad to 7075-T6 Unclad Aluminum</u>								
Room temperature	2788	2523	2671	2936	2408	2787	116 \pm 694	No change
260	2541	2178	2397	2437	2162	2274	-123 \pm 623	No change
<u>Magnesium to Magnesium</u>								
Room temperature	1343	1257	1310	1366	1084	1220	-90 \pm 341	No change
260	1329	1120	1208	1302	1132	1252	44 \pm 314	No change
<u>Fluid-Immersion Lap-Shear Tests</u>								
<u>2024-T3 Clad to 2024-T3 Clad Aluminum</u>								
<u>Immersion Fluid</u>								
3 per cent salt water	2752	2456	2591	2792	2730	2676	-15 \pm 674	No change
Tap water	2646	2380	2548	2900	2345	2577	29 \pm 693	No change
Anti-fog fluid	3116	2580	2738	3004	2402	2715	-20 \pm 711	No change
Hydraulic oil	2952	2635	2721	2910	2280	2623	-98 \pm 707	No change
JP-4 fuel	2766	2495	2617	2923	2676	2791	34 \pm 690	No change
Hydrocarbon Type III fuel	2608	2392	2536	3000	2276	2751	180 \pm 640	No change

(a) Irradiated in air to 2.4×10^9 ergs g⁻¹ (c.) (8×10^{14} nrvt, 6×10^{13} nrvt, and 5×10^{10} gammas/cm²).

(b) P = precision at 95 per cent confidence interval.

TABLE A-10. EFFECT OF 75 F IRRADIATION ON TENSILE-SHEAR STRENGTH, BEND STRENGTH, AND FATIGUE RESISTANCE OF CYCLEWELD C-6 ADHESIVE (MODIFIED NYLON-PHENOLIC) TESTED AT 75, 180, AND 260 F (10)

Tensile-Shear Strength

Temperature, F	Radiation Dose		Shear Strength, σ		σ (S)		Adjusted Shear Strength ^(a) , σ		σ (T)	
	$\times 10^{-7}$	$\text{ergs g}^{-1} (\text{C})$	psi	psi	psi	psi	psi	psi	psi	psi
Room temperature	0	0	2160	419	0.19	406	0.21			
	9.4	2.2×10^9	2190	209	0.10	234	0.11			
	35	3.1×10^{10}	2660	354	0.17	396	0.19			
	106	9.2×10^{10}	2510	843	0.34	247	0.36	2970	205	0.07
180	11.1	5.7×10^9	860	104	0.12	116	0.13			
	35	3.1×10^{10}	700	156	0.27	174	0.25			
	106	9.2×10^{10}	270	79	0.29	68	0.32			
260	10.7	9.3×10^9	400	91	0.24	107	0.27	440	41	0.09
	28	2.4×10^{10}	170	41	0.24	46	0.27			
	106	9.2×10^{10}	60	24	0.42	27	0.45			

Bend Strength

Temperature, F	Radiation Dose		Bend Strength, σ		σ (S)		σ (B)	
	$\times 10^{-7}$	$\text{ergs g}^{-1} (\text{C})$	lb	lb	lb	lb	lb	lb
Room temperature	0	0	194	13.1	0.07	14.7	0.08	
	10.7	9.3×10^9	167	28.8	0.17	32.2	0.19	
	35.5	3.1×10^{10}	165	26.1	0.16	29.2	0.18	
	106	9.2×10^{10}	151	42.3	0.29	47.3	0.31	
180	10.7	9.3×10^9	166	14.1	0.08	15.8	0.10	
	28	2.4×10^{10}	131	31.0	0.24	34.7	0.26	
	88	7.7×10^{10}	44	7.2	0.16	8.0	0.12	
260	10.7	9.3×10^9	97	15.9	0.16	17.8	0.18	
	35	3.1×10^{10}	35	13.7	0.38	14.8	0.42	
	106	9.2×10^{10}	13	4.4	0.34	5.0	0.38	

Fatigue Strength

Temperature, F	Radiation Dose		Load, psi	Cycles $\times 10^{-3}$	Type of Failure
	$\times 10^{-7}$	$\text{ergs g}^{-1} (\text{C})$			
Room temperature	0	0	1330	13	Adhesive
			1600		Failed while loading
			1066	656	Adhesive
			800	10,000	None
	11.1	9.7×10^9	933	10,000	None
	106	9.2×10^{10}	1066	233	Adhesive
			800	8374	Adhesive
			933	2889	Adhesive
			1333	146	Adhesive
			933	430	Adhesive

(a) σ - standard deviation of the group, computed according to the equation:

$$\sigma = \sqrt{\frac{\sum (x - \bar{x})^2}{N}}$$

where

x - strength test value of particular specimen

\bar{x} - arithmetical average of the five specimens undergoing a particular test

N - number of specimens in the group.

(b) (S) - shear strength, psi.

(c) σ - standard deviation corrected to account for the small number of specimens in each group, computed by means of the relation:

$$\sigma = \sigma \sqrt{\frac{N}{N-1}}$$

(d) in cases where one of the five test values deviated excessively from the average, it was discarded. The adjusted strength is the average with the extreme value discarded.

(e) (T) - adjusted shear strength, psi.

(f) (B) - bend strength, lb.

TABLE A-11. EFFECT OF HIGH-VELOCITY ELECTRON IRRADIATION ON SHEAR STRENGTH, PER CENT FLOW, AND VOLATILES FORMATION OF EPOXY ADHESIVES, WITH AND WITHOUT CALCIUM CARBONATE FILLER⁽³⁴⁾

Total Quantity of Radiation, watt-sec/cm ²	Radiation Absorbed		Approximate Equivalent Radiation, n/cm ²	Shear Strength(a) psi	Flow Under Load(b), per cent	Volatiles(c)
	megarep	ergs g ⁻¹				
<u>Epon 828, Unfilled(d)</u>						
0	0	0	0	5200	7	None
97	10	8.5 x 10 ⁸	1 x 10 ¹⁶	5300	0	None
201	30	2.5 x 10 ⁹	3 x 10 ¹⁶	6000	8	None
970	100	8.5 x 10 ⁹	1 x 10 ¹⁷	6300	0	None
2910	300	2.5 x 10 ¹⁰	3 x 10 ¹⁷	4200	10	None
9700	1000	8.5 x 10 ¹⁰	1 x 10 ¹⁸	2700	18	None
<u>P-11 (Epon 828, Calcium Carbonate Filler)(e)</u>						
0	0	0	0	3400	0	None
97	10	8.5 x 10 ⁸	1 x 10 ¹⁶	3900	1	None
201	30	2.5 x 10 ⁹	3 x 10 ¹⁶	3900	44	None
970	100	8.5 x 10 ⁹	1 x 10 ¹⁷	3300	6	None
2910	300	2.5 x 10 ¹⁰	3 x 10 ¹⁷	3800	7	None
9700	1000	8.5 x 10 ¹⁰	1 x 10 ¹⁸	3300	10	Trace
<u>Armstrong A-6, Unfilled(f)</u>						
0	0	0	0	4800	12	Slight
97	10	8.5 x 10 ⁸	1 x 10 ¹⁶	7700	16	Moderate
201	30	2.5 x 10 ⁹	3 x 10 ¹⁶	8500	4	Heavy
970	100	8.5 x 10 ⁹	1 x 10 ¹⁷	8700	6	Heavy
2910	300	2.5 x 10 ¹⁰	3 x 10 ¹⁷	5800	10	Heavy
9700	1000	8.5 x 10 ¹⁰	1 x 10 ¹⁸	2000	26	Heavy

Footnotes appear on the following page.

Footnotes for Table A-11.

(a) Preparation of Samples and Procedure:

- (1) Prepare 3 x 1 x 1/32-inch 2024-T3 aluminum strips by immersing for 10 minutes at 160 F in a solution of 340 parts by weight water, 50 parts sulfuric acid, and 10 parts sodium dichromate. Rinse for 15 minutes in running tap water, dip in methyl alcohol, and air dry.
- (2) Prepare shear samples by bonding 1/4 x 1/4-inch overlap sections. Oven cure as indicated under a load of 1 kilogram. Pull specimens apart in shear on Model L-6 Scott Tester with a draw separation speed of 1 inch per minute. The figures given are the average of six samples.

(b) Preparation of samples

Coat clean 3 x 1/4 x 1/32-inch 2024-T3 aluminum strips for one-half their length by dipping or brushing and cure.

Place the droplet end of the strip under a compression of 15 pounds in an oven at 250 F for 24 hr. Calculate the flow as follows:

$$\text{Flow} = \frac{\text{Decrease in droplet size} \times 100}{\text{Initial thickness of droplet and strip} - \text{thickness of strip}}$$

Each value listed is the average flow of two samples.

- (c) Prepare strips as above. Seal in glass tubes under 1 atmosphere of helium and store in an air oven at 250 F for 10 days. Remove and observe for any materials on the sides of the tube; this is assumed to be condensed volatile material from the resin tested.

(d) Composition by Weight:

Epon 828	100
Piperidine	7.5

Cure: Oven cure 2 hr at 200 F
plus 6 hr at 212 F

(e) Composition of P-11 by Weight:

Epon 828	100
Urethane (C ₆ H ₄ O ₂)	200
Piperidine	10

Cure: 8 hr at 212 F
plus 40 hr at 300 F

(f) Composition by Weight:

Armstrong A-6	100
Activator E	8

Cure: Oven cure for
2 hr at 200 F

TABLE A-12. EFFECT OF RADIATION ON TENSILE-SHEAR STRENGTH
OF EPOXY ADHESIVE, EPON VI(a, b)(35)

Gamma Exposure Dose, ergs g ⁻¹ (C)	Number of Specimens	Tensile-Shear Strength, psi	
		Range	Average
None	10	3070 - 3080	3027
0.4×10^9	3	3200 - 3075	3023
1.7×10^{10}	3	2710 - 3010	2870

(a) Radiation exposure and shear tests conducted at ambient temperatures.

(b) Cure: 200 F, 90 min, 10 psi.

TABLE A-13. EFFECT OF 75 F IRRADIATION ON TENSILE-SHEAR STRENGTH, BEND STRENGTH, AND FATIGUE RESISTANCE OF EPON VIII (EPOXY) TESTED AT 75, 180, AND 260 F (10, 32)

Tensile-Shear Strength

Temperature, F	Radiation Dose		Shear Strength, psi	$\sigma^{(a)}$		$\sigma^{(c)}$	
	$\times 10^{-2}$	mps $\text{g}^{-1} (\text{C})$		psi	$\sigma^{(b)}$	psi	$\sigma^{(d)}$
Room temperature	0	0	3430	91	0.03	102	0.03
	7.5	6.5×10^9	3490	127	0.03	137	0.24
	74	2.1×10^{10}	3130	179	0.04	140	0.45
	74	6.4×10^{10}	2250	200	0.09	224	0.10
100	6.6	5.7×10^9	3280	298	0.09	333	0.10
	25	2.2×10^{10}	3170	212	0.07	237	0.07
	63	5.5×10^{10}	1780	155	0.09	173	0.10
260	7.5	6.5×10^9	1350	140	0.10	157	0.12
	70	1.7×10^{10}	980	145	0.15	162	0.16
	78	5.8×10^{10}	440	37	0.07	36	0.08

Body Strength

Temperature F	Radiation Dose		Bond Strength, lb	λ , in	α (60°)	λ , in	α (60°)
	$\times 10^{-2}$	$\text{ergs cm}^{-1}(\text{C})$					
Room temperature	0	0	166	11.7	0.07	13.1	0.08
	1.6	6.6×10^9	150	13.7	0.09	15.1	0.10
	74	2.1×10^{10}	141	11.0	0.08	12.1	0.09
	65	5.7×10^{10}	117	4.3	0.04	4.8	0.04
180	1.6	6.6×10^9	167	10.7	0.06	11.4	0.07
	25	2.7×10^{10}	177	12.7	0.03	14.7	0.08
	74	6.4×10^{10}	154	7.9	0.05	8.8	0.06
260	1.6	6.6×10^9	57	7.1	0.07	8.0	0.07
	20	1.7×10^{10}	90	6.1	0.07	7.2	0.08
	74	6.8×10^{10}	48	4.4	0.04	5.0	0.05

Fatigue Strength

Temperature, °C	Radiation Dose		Time, min	Cycles x 10 ⁻³	Type of Fertilizer
	10^{-3}	$\text{ergs cm}^{-2} \text{ sec}^{-1}$			
Room temperature	0	0	11	5.74	Aphidivore
			15	1005	Aphidivore
			16.75	9188	Aphidivore
			1405	10,000	None
	6.4	5.4×10^9	16.75	890	Aphidivore
			15.45	1576	Aphidivore
			14.05	1986	Aphidivore
			12.05	14,000	Aphidivore
	28	6.0×10^{10}	16.75	357	Aphidivore
			15.45	1586	Aphidivore
20°C			14.05	1183	Aphidivore
			2405	14,000	None
			15.45	11,000	None

Note: Figure VIII, Capital Charge and Capitalization, legend wherever you find it on 10/28/17.

(a) is a finite difference approximation, calculated according to the equation

Abstract: This paper presents a study of the effect of the use of a computer-aided design (CAD) system on the design of a mechanical part. The study is based on a comparison of the design process using a CAD system with the design process using a traditional design method. The results of the study show that the use of a CAD system can significantly reduce the time and cost of the design process. The study also shows that the use of a CAD system can improve the quality of the design. The study is based on a comparison of the design process using a CAD system with the design process using a traditional design method. The results of the study show that the use of a CAD system can significantly reduce the time and cost of the design process. The study also shows that the use of a CAD system can improve the quality of the design.

^a Value of the average of the five years for each subgroup population (total)
$$b_1 = b_2 = \dots = b_{n-1} = 0, \quad b_n = 1.$$

and the other two are

TABLE 6. Standard deviations of predicted values computed from the regression model of log-transformed catch per unit effort ($\log_{10} CUE$) as a function of log-transformed abundance ($\log_{10} N$)

1. *Chlorophyll a* (Chl *a*)

• **11. How's the weather?**

TABLE A-14. EFFECT OF IRRADIATION ON LAP-SHEAR STRENGTH OF EPON VIII(10,32)

Radiation Source	Radiation Dose		Average Shear Strength, psi	$\bar{\sigma}(a)$, psi	$\bar{\sigma}(s)(b)$, psi	Adjusted Shear Strength(c), psi	$\bar{\sigma}(a)$, psi	$\bar{\sigma}(T)(d)$, psi	Per Cent of Original	Failure, Estimated Per Cent Adhesive
	rep	$\times 10^{-1}$	$\text{ergs cm}^{-2} (G)$							
Beta(B)	0	0	0			2267	110	0.049	100	10
	5	4.2 x 10 ⁹				2350	135	0.046	103.7	10
	20	1.7 x 10 ¹⁰				2124	99	0.049	93.7	20
	40	3.4 x 10 ¹⁰				1841	138	0.11	81.2	20
	60	5.1 x 10 ¹⁰				1632	457	0.23	72.4	70
Gamma	75	6.8 x 10 ¹⁰				1437	527	0.37	63.4	50
	0	0				3385	25.3	0.00729	100	10
	24	2 x 10 ¹⁰				3023	33	0.0098	89.3	30
	40	3.4 x 10 ¹⁰				2780	5.8	0.0021	82.1	20
	50	4.2 x 10 ¹⁰				2571	37	0.014	78.9	10

Note: Radiation and tests conducted at room temperature.

Lap-shear specimens from 20-mil 2024-T3 aluminum bonded to 63 mils irradiated through 20-mil strip. 20-mil strips reinforced with 53-mil strips prior to breaking.

(a) $\bar{\sigma}$ = corrected standard deviation of the group, computed according to the equation: $\bar{\sigma} = \frac{\sqrt{1-\frac{1}{N}}}{\sqrt{N-1}}$ where N = strength-test value of particular specimen

$\bar{\sigma}$ = arithmetical average of the five specimens undergoing a particular test

N = number of specimens in the group.

(b) (S) = shear strength, psi.

(c) In cases where one of the five test values deviated by greater than 3 (being calculated for the remaining four values), this value was discarded and the new average was listed as the "adjusted" figure for the group of four.

(d) (T) = adjusted shear strength, psi.

TABLE A-15. EFFECT OF 75 F IRRADIATION ON TENSILE SHEAR STRENGTH, BEND STRENGTH, AND FATIGUE RESISTANCE OF CYCLEWELD C-14 ADHESIVE (EPOXY) TESTED AT 75, 180, AND 260 F (10)

Temperature, F	Radiation Dose		Shear Strength		σ (a)		σ_y (c)		Adjusted Shear Strength (d)		σ_y		σ_y	
	$\times 10^7$	$\text{ergs g}^{-1} (\text{Ci})$	psi	ksi	σ_y (b)	psi	σ_y (b)	psi	psi	σ_y (b)	psi	σ_y (b)	psi	σ_y (b)
Room temperature	0	0	2710	562	0.21	628	0.23							
	10.7	9.3×10^9	2460	455	1.18	509	0.21							
	33	2.9×10^{10}	2490	557	0.22	623	0.25	1220	139	0.06	161	0.07		
	121	1.1×10^{11}	110	94	0.22	108	0.24							
180	9.7	8×10^9	160	56	0.35	63	0.39							
	33	2.9×10^{10}	100	22	0.22	25	0.25							
	121	1.1×10^{11}	45	5	0.11	6	0.13							
260	10.7	9.3×10^9	70	34	0.48	34	0.54							
	33	2.9×10^{10}	60	30	0.50	34	0.57							
	121	1.1×10^{11}	70	9	0.45	10	0.50							

Bend Strength

Temperature, F	Radiation Dose		Bend Strength		σ (a)		σ_y (c)	
	$\times 10^7$	$\text{ergs g}^{-1} (\text{Ci})$	lb	in	σ_y (b)	lb	σ_y (b)	in
Room temperature	0	0	161	32.4	0.20	36.2	0.22	
	9.7	8×10^9	131	21.4	0.16	23.6	0.18	
	33	2.9×10^{10}	129	28.0	0.27	31.3	0.24	
	121	1.1×10^{11}	24	5.9	0.24	6.6	0.28	
180	10.7	9.3×10^9	42	8.6	0.20	9.6	0.23	
	33	2.9×10^{10}	44	10.1	0.23	11.3	0.26	
	107.5	9.4×10^{10}	16	7.5	0.47	8.4	0.57	
260	10.7	9.3×10^9	15	7.7	0.51	8.6	0.57	
	33	2.9×10^{10}	8	5.3	0.69	6.1	0.76	
	121	1.1×10^{11}	3	2.7	0.77	2.6	0.83	

Fatigue Strength

Temperature, F	Radiation Dose		Cycles (psi)	Type of Failure
	$\times 10^7$	$\text{ergs g}^{-1} (\text{Ci})$		
Room temperature	0	0	1000	33 Adhesive
			1333	137 Adhesive
			1066	Failed while loading
			1856	584 Adhesive
			800	1316 Adhesive
107.5	9.4	10^{10}	150	1087 Adhesive
			400	Failed while loading
			250	
			200	

(a) σ Standard deviation of the group, computed according to the equation:

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}}$$

where
 x_i = strength test value of individual specimen
 \bar{x} = arithmetical average of the five specimens comprising a particular test
 n = number of specimens in the group

(b) σ_y Shear strength, psi

(c) σ_y Standard deviation corrected to account for the small number of specimens in each group, computed by use of the relation:

$$\sigma_y = \sigma \sqrt{\frac{n-1}{n-2}}$$

(d) In cases where one of the five test values deviated more than 10% from the average, it was discarded. The adjusted strength is the average with the extreme value discarded.

(e) (f) Adjusted shear strength, psi

(f) (g) Bend strength, psi

TABLE A-16. EFFECT OF HIGH-VELOCITY ELECTRON IRRADIATION ON SHEAR STRENGTH, PER CENT FLOW, AND VOLATILES FORMATION OF EPOXY-THIOL ADHESIVES, WITH AND WITHOUT CALCIUM CARBONATE FILLER^(3,4)

Radiation Absorbed ^(a) , crg g ⁻¹	Shear Strength, ^(b) psi	Flow Under Load ^(c) per cent	Volatiles ^(d)
<u>FA-1 (Epon 828, Thiolol)(e)</u>			
0	3500	11	None
2.5×10^9	3600	22	None
8.5×10^9	3700	10	None
2.5×10^{10}	3000	21	None
8.5×10^{10}	1700	17	None
<u>LCA-1 (Epon 828, Thiolol, Calcium Carbonate)(f)</u>			
0	2400	6	None
2.5×10^9	3000	8	Slight
8.5×10^9	2900	7	Slight
2.5×10^{10}	3000	16	Moderate
8.5×10^{10}	2000	19	Moderate
<u>FA-2 (Armstrong C-1, Thiolol)(g)</u>			
0	5100	11	Trace
8.5×10^8	5000	24	Moderate
2.5×10^9	5000	14	Slight
8.5×10^9	5000	25	Moderate
2.5×10^{10}	5700	38	None
8.5×10^{10}	1800	48	None
<u>LCA-2 (Armstrong C-1, Thiolol, Calcium Carbonate)(h)</u>			
0	3900	3	Trace
8.5×10^8	4500	12	Slight
2.5×10^9	4200	5	Slight
8.5×10^9	3800	9	Slight
2.5×10^{10}	2900	13	Moderate
8.5×10^{10}	1800	19	Heavy

Footnotes appear on the following page.

Footnotes for Table A-16.

- (a) For more complete information as to dose in watt-sec/cm² see Table A-9.
 (b) Preparation of samples and procedure:

- (1) Prepare 3 x 1 x 1/32-inch 2024-T3 aluminum strips by immersing for 10 minutes at 160 F in a solution of 340 parts by weight water, 50 parts sulfuric acid, and 10 parts sodium dichromate. Rinse for 15 minutes in running tap water, dip in methyl alcohol, and air dry.
- (2) Prepare shear samples by bonding 1/4 x 1/4-inch overlap sections. Oven cure as indicated under a load of 1 kilogram. Pull specimens apart in shear on Model L-6 Scott Tester with a draw separation speed of 1 inch per minute. The figures given are the average of six samples.

(c) Preparation of samples:

Coat clean 3 x 1/4 x 1/32 2024-T3 aluminum strips for one-half their length by dipping or brushing and cure.

Place the droplet end of the strip under a compression of 15 pounds in an oven at 250 F for 24 hr. Calculate the flow as follows:

$$\text{Flow} = \frac{\text{Decrease in droplet size} \times 100}{\text{Initial thickness of droplet and strip} - \text{thickness of strip}}$$

Each value listed is the average flow of two samples.

- (d) Prepare strips as above. Seal in glass tubes under 1 atmosphere of helium and store in an air oven at 250 F for 10 days. Remove and observe for any materials on the sides of the tube; this is assumed to be condensed volatile material from the resin tested.

(e) Composition by Weight:

Epon 828	100
Thiokol LP-2	25
DMP-30	4

(f) Composition by Weight:

Epon 828	100
Thiokol LP-2	25
Lesamite (CaCO ₃)	250
DMP-30	4

(g) Composition by Weight:

Armstrong C-1	100
Thiokol LP-2	20
Activator A	8

(h) Composition by Weight:

Armstrong C-1	100
Thiokol LP-2	20
Lesamite (CaCO ₃)	340
Activator A	8

TABLE A-17. EFFECT OF MIXED-FIELD IRRADIATION ON LASTILOK 620 (NITRILE RUBBER-PHENOLIC) LAP-SHEAR SAMPLES BONDING ALUMINUM AND MAGNESIUM^(a)

Temperature, F	Tensile-Shear Strength, psi						$X_1 - X_C \pm P^{(b)}$	Interpretation
	Control(X_C)			Irradiated (X_1) ^(a)				
	Maximum	Minimum	Mean	Maximum	Minimum	Mean		
<u>2024-T3 Clad to 2024-T3 Clad Aluminum</u>								
Room temperature	4843	3776	4338	4913	1156	4505	167 ± 1128	No change
280	2392	1956	2141	2543	2012	2248	107 ± 557	No change
<u>7075-T6 Unclad to 7075-T6 Unclad Aluminum</u>								
Room temperature	4804	4520	4645	5240	4921	5115	473 ± 1208	No change
280	2419	1980	2302	2493	2188	2380	78 ± 599	No change
<u>Magnesium to Magnesium</u>								
Room temperature	1792	1478	1698	1884	933	1208	-400 ± 441	No change
280	832	612	727	955	633	821	94 ± 189	No change
<u>Magnesium to 2024-T3 Clad Aluminum</u>								
Room temperature	2235	1109	1630	1920	810	940	-990 ± 425	Decrease
280	570	404	507	872	488	537	80 ± 132	No change
<u>Fluid-Immersion Lap-Shear Test</u>								
<u>2024-T3 Clad to 2024-T3 Clad Aluminum</u>								
<u>Immersion Fluid</u>								
4 per cent salt water	4570	3780	4242	4592	3780	4385	143 ± 1103	No change
Tap water	4700	3852	4231	4506	3706	4347	80 ± 1113	No change
Anti-icing fluid	4765	3509	4317	4820	4025	4484	167 ± 1122	No change
Hydraulic oil	4720	3016	4305	4717	4080	4423	214 ± 1093	No change
JP-4 fuel	4658	4073	4354	4764	3843	4417	63 ± 1132	No change
Hydrocarbon Type III fuel	4680	3348	4274	4740	3846	4480	206 ± 1111	No change

(a) Irradiated in air to 2.4×10^{11} ergs g^{-1} (C) (6×10^{14} n_{pt}, 6×10^{13} n_{vt}, and 5×10^{16} gammas/cm²).

(b) Precision at 25 per cent confidence interval.

TABLE A-18. EFFECT OF 75 F IRRADIATION ON TENSILE-SHEAR STRENGTH, BEND STRENGTH, AND FATIGUE RESISTANCE OF SCOTCHWELD AF-6 ADHESIVE (PHENOLIC) TESTED AT 75, 180, AND 260 F (10)

Tensile-Shear Strength										
Temperature, F	Radiation Dose		Shear Strength, psi	σ (a)		σ (c)		Adjusted Shear Strength (d) psi	σ , psi	$\sigma/(T)^{(e)}$
	$\times 10^{-7}$	$\text{eigs g}^{-1} (\text{C})$		psi	$\sigma/(S)^{(b)}$	psi	$\sigma/(S)^{(b)}$			
Room temperature	0	0	2920	151	9.05	169	0.06			
	7.6	6.6×10^9	3430	150	0.04	188	0.05			
	39	3.4×10^{10}	3990	105	0.02	117	0.03			
	74	6.4×10^{10}	3100	157	0.05	176	0.06			
180	7.6	6.6×10^9	1420	271	0.19	301	0.21			
	24	2.1×10^{10}	1860	596	0.32	666	0.36	7150	83	0.04
	74	6.4×10^{10}	1470	286	0.20	320	0.22			
260	7.6	6.6×10^9	1130	590	0.44	559	0.49			
	24	2.1×10^{10}	1060	238	0.27	322	0.31			
	63	5.5×10^{10}	1010	386	0.37	432	0.42			
Bend Strength										
Temperature, F	Radiation Dose		Bend Strength, lb	σ (a)		σ (c)		Adjusted Bend Strength (d) lb	σ , lb	$\sigma/(T)^{(e)}$
	$\times 10^{-7}$	$\text{eigs g}^{-1} (\text{C})$		lb	$\sigma/(B)^{(b)}$	lb	$\sigma/(B)^{(b)}$			
Room temperature	0	0	206	10.7	0.02	12.0	0.06			
	7.6	6.6×10^9	197	16.2	0.08	18.1	0.09			
	24	2.1×10^{10}	186	25.6	0.14	28.6	0.15			
	74	6.4×10^{10}	121	15.3	0.11	17.1	0.14			
180	7.6	6.6×10^9	133	27.5	0.21	30.9	0.23	146	4.2	0.06
	24	2.1×10^{10}	114	27.8	0.24	31.1	0.25	128	4.4	0.01
	74	6.4×10^{10}	106	11.8	0.11	13.2	0.12			
260	10.7	9.4×10^9	89	31.0	0.35	34.6	0.39	103	12.1	0.12
	20	1.7×10^{10}	66	22.2	0.34	24.8	0.38			
	63	5.5×10^{10}	55	10.3	0.19	11.5	0.21			
Fatigue Strength										
Temperature, F	Radiation Dose		Load, psi	Cycles $\times 10^4$	Type of Failure					
	$\times 10^{-7}$	$\text{eigs g}^{-1} (\text{C})$								
Room temperature	0	0	1600	218	Adhesive					
			1335	758	Adhesive					
			1200	1,264	Adhesive					
			1065	6,415	Adhesive					
			935	13,000	None					
	10.7	9.3×10^9	1315	1,911	Metal					
			1315	7,231	Metal and adhesive					
			1335	14,643	Adhesive					
			1200	1,096	Adhesive					
			1065	10,000	None					
	74	6.4×10^{10}	1335	170	Adhesive					
			1200	"	Adhesive					
			1200	"	Adhesive					
			1065	1,400	Adhesive					
			935	20,000	None					

(a) σ standard deviation of the group, computed according to the equation

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N-1}}$$

where

x_i = strength test value of individual specimen

\bar{x} = arithmetic average of the five specimens

N = number of specimens in the group

(b) (S) shear strength, psi

(c) σ standard deviation corrected to account for the small number of specimens in each group, computed by means of the relation

$$\sigma_c = \sigma \sqrt{\frac{N}{N-1}}$$

(d) In cases where one of the five test values deviated excessively from the average, it was discarded. The adjusted strength is the average with the extreme value discarded.

(e) (T) adjusted tensile strength, psi

(f) (B) bend strength, lb

(g) (D) adjusted bend strength, lb

TABLE A-10. EFFECT OF 75 F IRRADIATION ON TENSILE-SHEAR STRENGTH, BOND STRENGTH, AND FATIGUE RESISTANCE OF CYCLEWELD A-Z ADHESIVE (NITRILE RUBBER-PHENOLIC) TESTED AT 75, 180, 260, AND 500 F (10)

Tensile Shear Strength											
Temperature, °C	Radiation Dose		Shear Strength, psi	σ (a)				Adjusted Shear Strength(d)			
	$r \times 10^{-7}$	ergs g ⁻¹ (C)		psi	σ (SY) ^(b)	psi	σ (SY) ^(b)	psi	σ, psi	σ/(T) ^(e)	σ ₀ /(T) ^(e)
Room temperature	0	0	2030	192	0.09	215	0.10				
	10.5	9.2×10^9	1570	423	0.27	473	0.30				
	32	2.8×10^{10}	1920	495	0.26	553	0.29				
	107	9.3×10^{10}	1360	416	0.31	455	0.34				
180	10.5	9.2×10^9	770	374	0.49	418	0.54	590	66	0.11	76
	26	2.3×10^{10}	790	464	0.59	519	0.66	560	26	0.05	30
	81	7.1×10^{10}	1480	282	0.19	315	0.21				
260	10.5	9.2×10^9	880	386	0.44	432	0.49				
	26	2.3×10^{10}	460	50	0.11	56	0.12				
	99	8.6×10^{10}	880	133	0.15	149	0.17				
500	10.5	9.2×10^9	430	96	0.24	107	0.27				
	32	2.8×10^{10}	250	70	0.28	78	0.31				
	81	7.1×10^{10}	370	165	0.44	184	0.50				

Temperature, °F	Radiation Dose		Bond Strength						Adjusted Bond Strength(d)				
	$r \times 10^{-7}$	ergs g ⁻¹ (C)	Bond Strength, lb	σ (a), lb	σ (b) (B/ft)	σ (c), lb	σ (c) (B/ft)	lb	σ , lb	σ (f) (D/ft)	σ , lb	σ (g) (D/ft)	
Room temperature	0	0	145	23.7	0.16	26.5	0.18						
	10.5	9.2×10^9	131	21.6	0.16	24.2	0.18						
	26	2.3×10^{10}	118	19.8	0.17	22.1	0.19	127	5.9	0.05	6.8	0.05	
	99	8.6×10^{10}	68	15.0	0.22	16.8	0.25						
180	8.9	7.8×10^9	54	5.9	0.11	6.8	0.12						
	26	2.3×10^{10}	35	4.6	0.13	5.1	0.15						
	81	7.1×10^{10}	55	24.2	0.40	27.0	0.44						
260	8.9	7.8×10^9	47	8.8	0.19	9.8	0.21						
	32	2.8×10^{10}	34	6.1	0.18	6.9	0.20						
	99	8.6×10^{10}	45	7.2	0.16	8.0	0.18						
500	8.9	7.8×10^9	25	4.7	0.19	5.3	0.21						
	32	2.8×10^{10}	20	8.7	0.44	9.7	0.43						
	120	1×10^{11}	3	1.3	0.26	1.5	0.30						

Temperature, °F	Radiation Dose		Fatigue Strength			
	$r \times 10^{-7}$	ergs g^{-1} (C)	Load, psi	Cycles, 10^3	Type of Failure	
Room temperature	0	0	1600	2	Adhesive	
			1066	4M	Adhesive	
			800	10,000	None	
			933	1,941	Metal	
			933	20,000	None	
	99	8.6×10^{10}	933	Failed while loading		
			666	633	Adhesive	
			533	10,000	None	
			600	20,000	None	
			800	10,000	None	

(a) σ = standard deviation of the group, computed according to the equation $\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N}}$

where x_i = strength test value of particular specimen

\bar{x} = arithmetical average of the five specimens undergoing a particular test

N = number of specimens in the group

(b) (S) = shear strength, psi

(c) σ = standard deviation corrected to account for low skill number of

specimens in each group, computed by means of P - relation

$N = 1$

(d) In cases where one of the five test values deviated excessively from the average, it was discarded. The adjusted strength is the average with the extreme value discarded.

(e) (T) = adjusted shear strength, psi

(f) (D) = bond strength, psi

(g) (D) = adjusted bond strength, psi

TABLE A-20. EFFECT OF IRRADIATION^(a) ON TENSILE-SHEAR STRENGTH OF EC 1245 AND METLBOND 4021 ADHESIVES (NITRILE RUBBER-PHENOLIC)^(b)(35)

Gamma Exposure Dose, ergs g ⁻¹ (C)	Number of Specimens	Tensile-Shear Strength, psi	
		Range	Average
<u>EC-1245(c)</u>			
None	3	4850 - 5250	5030
1 x 10 ¹⁰	3	3730 - 4450	4180
1.7 x 10 ¹⁰	3	4680 - 4800	4750
8.7 x 10 ¹⁰	3	1500 - 1700	1570
<u>Metlbond 4021(d)</u>			
None	4	4600 - 4800	4715
8.7 x 10 ⁹	3	4850 - 5050	4900
1 x 10 ¹⁰	3	3880 - 4200	4030
1.7 x 10 ¹⁰	3	4100 - 4180	4120

(a) Irradiation at ambient temperature.

(b) Cures:

EC-1245 325 F, 40 min, 50 psi

Metlbond 4021 350 F, 45 min, 100 psi.

(c) EC-1245 manufactured by Minnesota Mining & Manufacturing Co. as a liquid.

(d) Metlbond 4021 manufactured by Narmco, Inc., as liquid and as a tape.

TABLE A-21. EFFECT OF RADIATION ON TENSILE-SHEAR STRENGTH OF BONDMASTER 248 ADHESIVE (NITRILE RUBBER-EPOXY)^{(a, b)(35)}

Gamma Exposure Dose, ergs g ⁻¹ (C)	Number of Specimens	Tensile-Shear Strength, psi	
		Range	Average
None	4	3310 - 3450	3547
8.7×10^9	3	3100 - 3250	3120
8.7×10^{10}	3	1800 - 2150	2000

(a) Irradiation and tests at room temperature.

(b) Cure: 300 F, 60 min, 50 psi.

TABLE A-22. EFFECT OF 75 F IRRADIATION ON TENSILE SHEAR STRENGTH, BOND STRENGTH, AND FATIGUE RESISTANCE OF CYCLOWELD C-3 ADHESIVE (NEOPRENE RUBBER-PHENOLIC) TESTED AT 75, 180, AND 260 F (10)

Tensile Shear Strength

Temperature, F	Radiation Dose		Shear Strength, psi	σ (a), psi	$\sigma/(2\eta b)$	η (c), psi	$\sigma/(\eta b)$
	$\times 10^{-2}$	$\text{ergs g}^{-1} (\text{C})$					
Room temperature	0	0	2580	113	0.04	126	0.06
	11.1	9.7×10^9	1600	114	0.07	127	0.08
	27	2.4×10^{10}	1120	135	0.12	151	0.13
180	11.1	9.7×10^9	1310	78	0.06	87	0.07
	27	2.4×10^{10}	920	111	0.12	124	0.13
260	11.1	9.7×10^9	1140	129	0.11	124	0.13
	35	3.1×10^{10}	770	46	0.06	51	0.07

Bond Strength

Temperature, F	Radiation Dose		Bond Strength, lb	σ (a), lb	$\sigma/(B\eta d)$	η (c), lb	$\sigma/(\eta d)$	Adjusted Bond Strength (e), lb	σ , lb	$\sigma/(D\eta f)$	σ , lb	$\sigma/(D\eta f)$
	$\times 10^{-2}$	$\text{ergs g}^{-1} (\text{C})$										
Room temperature	0	0	203	7.9	0.04	8.9	0.04					
	11.1	9.7×10^9	114	7.4	0.06	8.3	0.07					
	35	3.1×10^{10}	67	11.7	0.12	13.0	0.19					
	90	7.0×10^{10}	38	13.4	0.35	15.0	0.39					
180	9.4	8.2×10^9	75	14.8	0.20	16.6	0.22					
	35	3.1×10^{10}	61	14.6	0.23	16.3	0.26	55	2.6	0.05	3.0	0.06
	106	7.7×10^{10}	4	6.2	1.55	6.9	1.72	0	0	0	0	0
260	9.4	8.2×10^9	68	23.6	0.35	26.3	0.39	57	10.4	0.18	12.0	0.21
	27	2.4×10^{10}	35	8.0	0.23	9.0	0.26					
	107.5	9.4×10^{10}	0	0	0	0	0					

Fatigue Strength

Temperature F	Radiation Dose		Load, psi	Cycles $\times 10^{-3}$	Type of Failure
	$\times 10^{-2}$	$\text{ergs g}^{-1} (\text{C})$			
Room temperature	0	0	1685	497	Metal
			1410	1,081	Metal
			1120	9,861	Metal
			1120	14,000	None
			1410	1706	Metal
107.5	9.4×10^{10}		All failed in handling		

(a) standard deviation of the group, computed according to the equation $\sigma = \sqrt{\frac{\sum (x - \bar{x})^2}{N}}$ where

x = strength test value of particular specimen
 \bar{x} = arithmetical average of the five specimens comprising a particular test
 N = number of specimens in the group.

(b) (5) shear strength, psi.

(c) σ = standard deviation corrected to account for the small number of specimens in each group, computed by means of the relation $\sigma = \sigma \sqrt{\frac{N}{N-1}}$.

(d) (1) bond strength, lb.

(e) In cases where one of the five test values deviated excessively from the average, it was discarded. The adjusted strength is the average with the extreme value discarded.

(f) (1) - adjusted bond strength, lb.

TABLE A-23. EFFECT OF RADIATION ON TENSILE-SHEAR STRENGTH OF METLBOND MN3C ADHESIVE (NEOPRENE RUBBER-NYLON-PHENOLIC)^(a, b)(35)

Gamma Exposure Dose, orgs g ⁻¹ (G)	Number of Specimens	Tensile-Shear Strength, psi Range	Average
<u>Metlbond MN3C (Liquid and Tape on Aluminum)</u>			
None	10	2980 - 3110	2878
0.4×10^9	3	1112 - 1160	1130
1.7×10^{10}	3	898 - 1082	1017
<u>Metlbond MN3C (Liquid and Tape on Magnesium)</u>			
None	10	1220 - 2000	1670
0.4×10^9	3	1018 - 1094	1057
1.7×10^{10}	3	707 - 1010	880

(a) Irradiation and tests conducted at room temperature.

(b) Cure: 325 F, 45 min, 40 psi.

TABLE A-24. EFFECT OF 75 F IRRADIATION ON TENSILE-SHEAR STRENGTH OF METLBOND MN3C ADHESIVE (NEOPRENE RUBBER-NYLON-PHENOLIC) TESTED AT 75 AND 180 F^(a)

Test Temperature, F	Tensile-Shear Strength, psi						$(X_I - X_C) \pm p^{(2)}$
	Control (X_C)			Irradiated (X_I) ^(a)			
	Maximum	Minimum	Mean	Maximum	Minimum	Mean	
<u>2024-T3 Clad to 2024-T3 Clad Aluminum</u>							
Room	3404	3008	3222	3256	2074	2060	-272±888
180	1581	1362	1616	1346	484	1183	-332±394
<u>7075-T6 Unclad to 7075-T6 Unclad Aluminum</u>							
Room	3188	2772	2987	3325	2816	3028	81±771
180	1561	1132	1297	1381	974	1102	-106±337
<u>Magnesium to Magnesium</u>							
Room	2184	1092	2051	1083	1565	1784	-267±633
180	1141	869	1006	878	735	792	-214±425

(a) Irradiated in air to 2.4×10^5 ergs g⁻¹ (C) (0×10^{14} nvt, 0×10^{13} nvt, 5×10^{16} rads/cm²).

(b) P = precision at 95 per cent confidence interval.

TABLE A-22. EVALUATION OF COATING SYSTEMS AFTER EXPOSURE TO A COBALT-60 GAMMA UNIT(27)

Systems (a)	Original Color and Gloss(b) of Topcoat	Effect of Indicated Exposure Dose on Coating Systems				Over-all Rating of System(c)
		8.7×10^9 Ergs G^{-1} (C) (3.9×10^7 Roentgens), 222 Hours	1.3×10^{10} Ergs G^{-1} (C) (1.5×10^8 Roentgens), 439 Hours	2.4×10^{10} Ergs G^{-1} (C) (3.3×10^8 Roentgens), 948 Hours	3.8×10^{10} Ergs G^{-1} (C) (4.3×10^8 Roentgens), 1380 Hours	
System 1 MIL-P-8555 zinc chromate primer (no topcoat)		No change	No change	No change	Slight darkening, otherwise OK	P
System 2 MIL-C-8514 wash primer MIL-P-8555 zinc chromate primer (no topcoat)		Slight embrittlement	Embrittlement of system	Moderate darkening, system very brittle	Moderate darkening, system very brittle	P
System 3 MIL-C-8514 wash primer MIL-P-7962 lacquer primer (no topcoat)		Slight embrittlement	Embrittlement of system	System very brittle	Slight darkening, system very brittle	P
System 4 MIL-C-8514 wash primer MIL-P-7962 lacquer primer MIL-L-19537 nitrocellulose- acrylic lacquer	Gloss white	Slight darkening, no change in film integrity	Not examined	Slight yellowing, system very brittle(d)	Not examined	P
System 5 MIL-C-8514 wash primer MIL-P-7962 lacquer primer MIL-L-19538 nitrocellulose- acrylic lacquer	Flat white	Slight yellowing, no change in film integrity	Slight darkening, system embrittled	Not examined	Yellowed, system embrittled(d)	P
System 6 MIL-C-8514 wash primer MIL-P-7962 lacquer primer MIL-L-1175 nitrocellulose lacquer	Gloss white	Slight yellowing, no change in film integrity	Not examined	Slight yellowing, system embrittled	Not examined	P

TABLE A-25. (Continued)

Effect of Indicated Exposure Dose on Coating Systems						
Systems (a)	Original Color and Gloss(b) of Topcoat	6.7×10^3 Ergs cm^{-2} (8.3×10^7 Roentgens), 228 Hours	1.9×10^{10} Ergs cm^{-2} (1.5×10^8 Roentgens), 430 Hours	2.9×10^{10} Ergs cm^{-2} (3.3×10^8 Roentgens), 943 Hours	3.8×10^{10} Ergs cm^{-2} (4.3×10^8 Roentgens), 1230 Hours	Over-all Rating of System (c)
System 7 MIL-C-8514 wash primer MIL-P-7962 lacquer primer MIL-L-006805 nitrocellulose lacquer	Flat white	Slight yellowing, no change in film integrity	Darker than MIL-L-19538 system, but only very slight embrittlement	Not examined	Darker than MIL-L-19538 system, system is now also brittle	P
System 8 MIL-C-8514 wash primer MIL-P-7962 lacquer primer AML experimental al-acrylic lacquer, 88C	Gloss white	No change in color, slight embrittlement	Excellent color retention, system very brittle	Not examined	Excellent color retention, system very brittle(e)	P
System 9 MIL-C-8514 wash primer MIL-P-8585 zinc chromate primer AML experimental coating 38B, silicone alkyd (air dry)	Gloss white	No change	Not examined	Color retention good, system slightly embrittled	Not examined	P
System 10 MIL-C-8514 wash primer MIL-P-8585 zinc chromate primer AML experimental coating 38C, silicone-alkyd (air dry)	Flat white	Slight darkening, otherwise OK	Not examined	Slight darkening, otherwise OK	Not examined	Pt
System 11 MIL-C-8514 wash primer MIL-P-8585 zinc chromate primer MIL-E-7729, Type I alkyd enamel	Gloss white	No change	No change	Not examined	Excellent color retention, topcoat soft and tacky (very poor print resistance), entire system easily cut from metal in soft strips	P
System 12 MIL-E-7729, Type I alkyd enamel (no primer undercoat)	Gloss white	No change	No change	Not examined	Same as above MIL-E-7729 Type I primer system	P

TABLE A-25. (Continued)

Effect of Indicated Exposure Dose on Coating Systems						
Systems (a)	Original Color and Gloss (b) of Topcoat	6.7×10^3 Ergs cm^{-2} (5.0×10^3 Roentgens), 208 Hours	1.3×10^{10} Ergs cm^{-2} (1.5×10^8 Roentgens), 453 Hours	2.9×10^{10} Ergs cm^{-2} (3.3×10^8 Roentgens), 943 Hours	3.8×10^{10} Ergs cm^{-2} (4.3×10^8 Roentgens), 1239 Hours	Overall Rating of System (c)
System 13 MIL-C-8814 wash primer MIL-P-8885 zinc chromate primer MIL-E-8886 alkyd enamel	Flat white	No change	No change	Not examined	No change except for slight darkening	P
System 14 MIL-E-7703, Type III high-bake alkyd enamel (no primer undercoat)	Gloss white	No change	Not examined	No change in color, slight embrittlement	Not examined	F
System 15 MIL-C-8814 wash primer Neoprene primer Neoprene topcoat	Yellow	Turned brown, loss of toughness in system (easily cut with knife)	Dark brown, loss of toughness of system	Dark brown, blistering noted	Dark brown, badly blistered and very brittle	P
System 16 ANIL experimental coating, P33, high bake alkyd silicone (no primer undercoat)	Semi-gloss white	Yellowed, otherwise OK	Not examined	Some degree of yellowing, otherwise OK	Not examined	P
System 17 ANIL experimental coating, P19, amine catalyzed epoxy (no primer undercoat)	Gloss white	Yellowed, otherwise OK	Yellow-brown, otherwise OK	Not examined	Burned brown, very brittle and poor adhesion to metal	P
System 18 Proprietary amine catalyzed epoxy (no primer undercoat)	Gloss white	Yellowed, otherwise OK	Not examined	Yellowed, otherwise OK	Not examined	P

TABLE A-25. (Continued)

Effect of Indicated Exposure Dose on Coating Systems						
System (a)	Original Color and Gloss (b) of Topcoat	5.7×10^3 Ergs G^{-1} (C) (8.0×10^4 Roentgens), 228 Hours	1.3×10^{10} Ergs G^{-1} (C) (1.3×10^3 Roentgens), 450 Hours	2.9×10^{16} Ergs G^{-1} (C) (3.3×10^5 Roentgens), 943 Hours	3.8×10^{16} Ergs G^{-1} (C) (4.5×10^5 Roentgens), 1220 Hours	Over-all rating of System (c)
System 13 MIL experimental coating, P22, versamid catalyzed Upon (no primer undercoat)	Gloss white	Yellowed, darkening of film	Darkened, coating slightly embrittled	Not examined	Tan, coating embrittled	P
System 23 MIL-R-3343 high-base phenolic coating (no primer undercoat)	Amber	Darkened, otherwise OK	Dark bronze, other- wise OK	Not examined	Dark bronze, coating hardened, adhesion improved	P+

(a) Coating thicknesses of the wash primer and primer coatings were 0.2 mil and 0.4 mil respectively. All topcoats were sprayed to approximately 1.0 mil (dry film thickness) with the exception of the neoprene coating which was brushed to a thickness of 11.0 mil.

(b) Quantitative gloss measurements could not be made because of the size of the specimens. In general, no significant reductions in gloss were apparent as the test progressed.

(c) P+ = promising

P = fair resistance

P- = poor resistance.

(d) Intermediate in brittleness between the nitrocellulose lacquers (Systems 5 and 7) and the all-acrylic lacquer (System 8).

(e) Most brittle of lacquers tested.

TABLE A-26. MANUFACTURERS OF ORGANIC PROTECTIVE COATINGS
AND GASKETS⁽³⁸⁾

	Manufacturer
Mounted Coatings	
Alkaloy-550, Amphesive-801, Ampreg-E, Neobon, Zerox-110	The Atlas Mineral Products Company Houston, Texas
Amercoat-23, -33, -44, -55 and -1574 SE	Amercoat Corporation South Gate, California
Barrett Silicone	Barrett Varnish Company Cicero, Illinois
Corrosite-22	Corrosite Corporation New York, New York
Duralon-36	U. S. Stoneware Akron, Ohio
Du Pont White	E. I. du Pont de Nemours and Company, Inc. Wilmington, Delaware
Dyna-clad	Merchants Chemical Company, Incorporated New York, New York
Epon-395	The Glidden Company Chicago, Illinois
Epon-1001	Shell Chemical Corporation New York, New York
Nukomite-40	Nukem Products Corporation Buffalo, New York
Phenoline-3, Polyclad Sealcoat	Carboline Company St. Louis, Missouri
Prufcoat	Prufcoat Laboratory, Incorporated Cambridge, Massachusetts
Solar Silicone Alkyd	Solar Corporation Milwaukee, Wisconsin
Ucilon	United Chromium, Incorporated New York, New York

TABLE A-26 (Continued)

	Manufacturer
Unmounted Coatings A-89-A-Black	Gordon-Lacey Chemical Products Company New York, New York
Amercoat Strip, Amerplate (T-Locked, Black and White)	Amercoat Corporation South Gate, California
Brevon-Black	Atlas Powder Company N. Chicago, Illinois
G. E. Cocoon	R. M. Hollingshead Corporation Camden, New Jersey
Tygofilm-Blue	U. S. Stoneware Akron, Ohio
Flame-Sprayed Polyethylene	The Powder Weld Process Company Brooklyn, New York

TABLE A-17 (Continued)

Coating	Polymer Base	Surface of Application	Total Gamma Dose, Mrads $\times 10^{-3}$ (C) $\times 10^{-5}$												Visual Postirradiation Observations
			0	1	2	3	4	5	6	7	8	9	10	11	
Neobion	Neoprene	Concrete Panel	[Hatched]												Hardened but no cracks or blisters Hardened on tip of rod
		Steel Immersion Rod	[Hatched]												
		Steel Immersion Rod - Wet	[Hatched]												
		Steel Panel	[Hatched]												
Neobion	Vinyl	Aluminum Panel	[Hatched]												Blistered Surface soft, gel formed
		Concrete Panel	[Hatched]												
		Steel Immersion Rod	[Hatched]												
		Steel Panel - Wet	[Hatched]												
Polyurethane	Polyurethane	Concrete Panel	[Hatched]												Freaky all joints color much darker Visible traces Visible traces
		Steel Immersion Rod	[Hatched]												
		Steel Panel - Wet	[Hatched]												
		Concrete Panel	[Hatched]												
Polyurethane	Styrene	Steel Immersion Rod	[Hatched]												Freaky all joints color much darker Visible traces Visible traces Surface badly wrinkled
		Steel Panel - Wet	[Hatched]												
		Concrete Panel	[Hatched]												
		Concrete Panel	[Hatched]												
Silicone	Silicone	Concrete Panel	[Hatched]												Hard, joint cracks, no blisters, hardened layer under surface Chipped, cracked, blistered Paint cracked from panel
		Steel Immersion Rod	[Hatched]												
		Steel Panel	[Hatched]												
		Steel Panel - Wet	[Hatched]												
Silicone	Silicone	Concrete Panel	[Hatched]												Surface blistered Extreme color change color darker
		Steel Immersion Rod	[Hatched]												
		Steel Panel	[Hatched]												
		Steel Panel - Wet	[Hatched]												

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3. \mathbb{Z}^2 is a free \mathbb{Z} -module of rank 2. $\mathbb{Z}^2 \otimes \mathbb{Z} = \mathbb{Z}^2$.

TABLE A-28. RESULTS OF CHEMICAL RESISTANCE AND DECONTAMINATION STUDIES ON MAINTAINED COATINGS (38)

Coating	Surface	Gamma Dose (R, γ)		Results (a)				Decontamination Factor
		Ergs G-I (C) $\times 10^{-9}$	Roentgens	Reagents	Acid	Base	Solvent C/D(b)	
Alkaid-10	Concrete	99.1	1.13×10^9	HNO ₃ -FP(c)				
	Steel	87.7	1.0×10^9	HNO ₃ , NaOH, hexone	R	R	R	25-200
Amercol-1-33	Aluminum	8.8	1.0×10^8	HNO ₃ -FP			R	70-117
Amphesive-801	Steel	87.7	1.0×10^9	HNO ₃ , NaOH, hexone	N	N	N	
Barrett Silicone	Concrete	70.2	8×10^8	HNO ₃ -FP			R	12
	Steel	70.2	8×10^8	HNO ₃ , HCl, NaOH, hexone, HNO ₃ -FP	N	N	N	
Corrosite-22	Aluminum	8.8	1×10^8	HNO ₃ -FP			R	500
Duralon-38	Concrete	87.7	1×10^9	HNO ₃ -FP			R	40-200
	Steel	87.7	1×10^9	HNO ₃ , NaOH, hexone, HNO ₃ -FP	R	R	N	
Epon-335	Steel	70.2	8×10^8	HNO ₃ , NaOH, HCl, H ₂ SO ₄ , hexone	R	R	R	200
Epon-1001	Concrete	105.2	1.2×10^9	HNO ₃ -FP			R	3
	Steel	70.2	8×10^8	HNO ₃ , NaOH, HCl, hexone, HNO ₃ -FP	R	R	N	
Neobon	Steel	87.7	1×10^9	HNO ₃ , NaOH, hexone, HNO ₃ -FP	R	R	N	3-8
Nukemite-40	Steel	87.7	1×10^9	HNO ₃ , NaOH, hexone	N	N	N	
Solar Silicone Alkyd Concrete	Concrete	70.2	8×10^8	HNO ₃ -FP			R	8-15
	Steel	70.2	8×10^8	HNO ₃ -FP			N	

(a) R = resistant

N = nonresistant.

(b) C/D = the process of HNO₃-fission product contamination and decontamination.

(c) FP = fission-product contaminant.

TABLE A-29. STUDIES OF RADIATION DAMAGE TO UNMOUNTED COATINGS (38)

[Gamma-Radiation Dosage = 5.2×10^{10} ergs g^{-1} (C) (1.65×10^9 roentgens) in air]

Coating	Polymer Base	Color Change	Flexibility	180° Bend Test	Remarks
Strip Coats					
A-89-A	Vinyl	Black, unchanged	Stiff	Breaks	Sample curled
Amercoat Strip	Vinyl	White to gray	Stiff	Breaks	Sample curled
Brevon	Vinyl	Black, unchanged	Stiff	Breaks	Sample curled
G. E. Cocoon	Vinyl copolymer	Orange to black	Flexible	Bends	Tacky surface
Tygofilm	Vinyl copolymer	Blue to gray	Stiff	Breaks	Not curled
Plastic Sheet					
Amer Plate	Vinyl	Black, unchanged	Stiff	Breaks	Not curled
(T-Locked, Black)					
Amer Plate	Polyethylene	White to amber	Stiff	Breaks	Not curled
(T-Locked, White)					
Polyethylene	Polyethylene	Red, yellow, and blue	Stiff	Breaks	Not curled
(Flame-Sprayed)		to darker shades			

TABLE A-30. SILICONE INSULATION SYSTEMS AND CONSTRUCTIONS(47)

<u>Motorette Insulation Systems</u>						
<u>Insulation System</u>	<u>Wire</u>	<u>Wire Insulation</u>	<u>Ground and Phase Insulation</u>	<u>Lead Insulation</u>	<u>Slot Sticks</u>	<u>Silicone Varnish</u>
A	AWG 18 copper	Double-glass silicone varnish Sylkyd ^(a) 1090 bond	Glass-mica-glass silicone bonded	Silicone-varnished glass sleeving	G-7 silicone-glass laminate	
B	AWG 18 copper	Double Daglas ^(b) Sylkyd 1090 bond	Glass-mica-glass silicone bonded	Silicone-rubber glass sleeving	G-7 silicone-glass laminate	Dow Corning 997
C	AWG 18 copper	Modified silicone enamel Sylkyd 1364	Glass-mica-glass silicone bonded	Silicone-varnished glass sleeving	G-7 silicone-glass laminate	
D	AWG 18 copper	Double Daglas Sylkyd 1090 bond	Glass-asbestos-glass silicone bonded	Silicone-varnished glass sleeving	G-7 silicone-glass laminate	
<u>Motor Insulation System</u>						
Motor	AWG 22 copper	Double-glass served, Sylkyd 1090 bond	Glass-mica-glass silicone bonded	Silastic-insulated lead wire	G-7 silicone-glass laminate	Dow Corning 997
<u>Formette Insulation Systems</u>						
<u>System</u>	<u>Conductor</u>	<u>Primary Insulation</u>	<u>Outer Wrap</u>	<u>Cure</u>	<u>Simulated Slot</u>	
E	1/4 x 3/4 x 4 in. aluminum	0.080-in. thick insulation made using 0.020-in. silicone rubber Silastic ^(a) 81 tape, Silastic S-2007 paste	Glass-reinforced, semi-vulcanized, silicone rubber tape, 0.020 in. thick	24 hr. 250 C.	0.010-in. aluminum foil, 4 in. wide	
F	6 stacked copper conductors, each 0.100 x 0.250 x 6 in., double-glass served, bonded with silicone varnish Sylkyd 1090	Conductors bonded with Silastic X 3-009B, 0.080-in. thick insulation made using Silastic S-6418 Guideline tape	Glass-reinforced semi-vulcanized, silicone rubber tape, 0.020 in. thick	16 hr. 200 C.	0.010-in. aluminum foil, 4 in. wide	
<u>Wire and Cable Construction</u>						
<u>Construction</u>	<u>Conductor</u>	<u>Insulation</u>				
G	No. 14 stranded copper	Silastic 80 (MIL-W-8777A Type MT-14 wire)				
H	No. 14 stranded copper	Silastic 80, 1/64-in. wall, vulcanized only				
I	No. 18 stranded copper	Silastic S-2070, 1/64-in. wall, vulcanized only				
J	3-No. 20 stranded copper	Silastic 916, 15-mil-wall conductor insulation, silicone-resin-impregnated braid; Silastic 916 cable jacket, 1/64-in. wall, postcured 4 hr at 480 F				

(a) Sylkyd is a Dow Corning trademark for silicone varnishes and enamels, Silastic is this company's trademark for silicone rubber.

(b) Daglas is a trade designation for glass-Dacron insulation

(a) Sylkyd is a Dow Corning trademark for silicone varnishes and enamels; Silastic is this company's trademark for silicone rubber.

(b) Daglas is a trade designation for glass-Dacron insulation.

TABLE A-31. HUMIDIFIED INSULATION RESISTANCE FOR SILICONE-INSULATED MOTORETTES EXPOSED TO RADIATION AT 200 C (47)

Conditioned 72 Hr at 30 C and 100 Per Cent RH

Exposure			Insulation Resistance, megohms								
Ergs G ⁻¹ (C)	Megarads	Hr at 200 C	System A(a)		System B		System C		System D		
x 10 ⁹			1	2	1	2	1	2	1	2	
<u>Phase-to-Phase</u>											
0	0	0	570	500	4000	700	13,000	4000	7500	5000	
3.2	35.2	760	70	00	40	140	2,000	3500	22	250	
9.2	101.4	2160	8.0	22	0.4	18	Units failed		0.15	12	
14.0	153.6	3200	14	22	04	57			10	2.8	
18.7	205.6	4360	230	500	600	500			24	0.9	
23.2	255.6	5420	3.0	1.6	120	90			5.0	1.4	
27.7	304.6	6460	24	3.0	410	18			16	0.1	
<u>Phase-to-Ground</u>											
0	0	0	430	200	1900	300	5500			800	2000
3.2	35.2	760	30	55	18	60	250			85	180
9.2	101.4	2160	11	38	115	13	Units failed		1.0	15	
14.0	153.6	3200	8.7	1.8	140	44			10	0.0	
18.7	205.6	4360	550	230	540	400			170	0.7	
23.2	255.6	5420	1.0	1.4	7.0	1.6			22	8.0	
27.7	304.6	6460	15	3.0	230	16			80	0.1	

Notes: Motorettes were removed periodically from exposure conditions for insulation measurements. Nominal exposure cycle (subject to some variation) was 50 megarads. Irradiated rate was approximately 0.05 megarad/hr. Samples irradiated at 200 C were exposed in a 1.0-cu ft convection oven at 200 ± 2 C. Oven was located adjacent to the radiation source. Positions of samples were periodically changed to obtain uniform radiation doses.

Test: Procedures were substantially the same as in AIEE No. 510. Motorettes were allowed to stabilize at room temperature after removal from exposure conditions. The 1-hr vibration period was followed by proof tests at 600 volts a-c phase-to-phase and phase-to-ground and also at 120 volts a-c turn-to-turn. Motorettes were then subjected to 100 per cent RH at 30 C for 72 hr. At the end of this humidification period (and while the motorettes were still in the humidity chamber) they were again proof-tested.

The red unit of exposure is equivalent to 100 ergs of absorbed energy per gram of absorbing material.

(a) See Table A-30 for System composition. Numerals 1 and 2 refer to number of motorette samples tested.

TABLE A-32. HUMIDIFIED INSULATION RESISTANCE FOR SILICONE-INSULATED MOTORETTES
EXPOSED TO RADIATION ONLY⁽⁴⁷⁾

Conditioned 72 Hr at 30 C and 100 Per Cent RH

Exposure		Insulation Resistance, megohms			
Ergs G ⁻¹ (C) x 10 ⁸	Megarads	System A ^(a)	System B	System C	System D
<u>Phase-to-Phase</u>					
0	0	1860	180	3000	2200
3.2	38.2	1200	12	380	1200
9.2	101.4	40	4	18	55
14.0	163.6	4.9	6.6	8	0.85
18.7	208.6	1.8	17	2.0	1.6
23.2	266.6	0.18	0.30	13.0	1.6
27.7	304.6	0.20	0.40	3.0	0.24
<u>Phase-to-Ground</u>					
0	0	680	120	850	1300
3.2	38.2	70	10	200	60
9.2	101.4	0.8	3.0	58	15
14.0	163.6	4.8	4.5	3.6	0.5
18.7	208.6	0.7	7.0	1.8	1.5
23.2	266.6	No reading	0.25	5.0	0.90
27.7	304.6	0.20	0.30	2.0	0.23

(a) See Table A-30 for System composition. See Table B-14 for test procedure.

TABLE A-33. EFFECTS OF GAMMA RADIATION AT ROOM TEMPERATURE ON SILICONE-RUBBER FORMETTE INSULATION SYSTEMS (47)

Insulation System(a)	Gamma Dose		Conditioned 24 Hrs at 23 C and 50% RH				Conditioned 48 Hr at 30 C and 100% RH			
	Ergs C ⁻¹ (C) x 10 ⁹	Megarads	7-Kv Proof Test	Insulation Resistance, megohms	50-C Capacitance, p	50-C Dissipation Factor	7-Kv Proof Test	Insulation Resistance, megohms	60-C Capacitance, p	60-C Dissipation Factor
F	0	0	OK	>10 ⁶	50	0.008	OK	>10 ⁶	68	0.050
	4.5	50	OK	>10 ⁶	52	0.019	OK	10 ⁶	74	0.050
	6.8	75	OK	>10 ⁶	62	0.010	OK	10 ⁶	68	0.050
	10.5	116.5	OK	>10 ⁶	66	0.008	OK	>10 ⁶	74	0.050
F	0	0	OK	>10 ⁶	46	0.014	OK	10 ⁶	52	0.050
	4.5	50	OK	>10 ⁶	47	0.012	OK	>10 ⁶	55	0.050
	6.8	75	OK	>10 ⁶	48	0.015	OK	>10 ⁶	58	0.050
	10.5	116.5	OK	>10 ⁶	52	0.007	OK	>10 ⁶	63	0.050

Notes: Test procedure used after each exposure cycle was essentially the same as that specified in AIEE Test Procedure No. 511 for 5-kv insulation systems. The formettes were allowed to stabilize at room temperature after removal from the exposure condition. Measurements were made between the foil and the conductor. Proof tests at 7-Kv, 60 cycles for 1 min were applied. Following a 1-hr vibration, the formettes were humidified at 100 per cent RH at 30°C for 48 hr. The measurements were repeated while the bars were still in the humidity chamber. The data were then returned to their respective exposure conditions.

(47) See Table A-30 for system composition.

TABLE A-34. EFFECTS OF GAMMA RADIATION AT 207°C ON SILICONE-RUBBER FORMLETTE INSULATION SYSTEMS (47)

Insulation System(a)	Gamma Dose Ergs cm^{-2} (G) $\times 10^{-4}$	Exposure, hr	Conditioned 24 Hr at 23 C and 50% RH					Conditioned 48 Hr at 30 C and 100% RH				
			7-Kv Proof Test	Insulation Resistance, megohms	50-C Capacitance, f	60-C Dissipation Factor	7-Kv Proof Test	Insulation Resistance, megohms	50-C Capacitance, f	60-C Dissipation Factor		
			OK	>10 ⁶	52	0.008	OK	>10 ⁵	60	0.056		
E	0	0	OK	>10 ⁶	52	0.008	OK	>10 ⁵	60	0.056	--	
	4.5	625	OK	>10 ⁶	54	0.010	OK	>10 ⁶	55	0.070		
	6.5	935	OK	>10 ⁶	43	0.010	OK	>10 ⁶	60	0.080		
F	0	0	Failed	--	--	--	Failed	--	--	--	--	
	0	0	OK	>10 ⁶	41	0.009	OK	10 ⁶	50	0.050		
	4.5	625	OK	>10 ⁶	45	0.009	OK	10 ⁶	53	0.050		
	6.5	935	OK	>10 ⁶	40	0.014	OK	>10 ⁶	40	0.012		
	0	0	Failed	--	42	0.008	OK	10 ⁶	45	0.023		
			4 kv	--	--	--	4 kv	--	--	--		

(a) See Table A-3 for system composition. See Table B-16 for test procedure.

TABLE 35. DIELECTRIC PROPERTIES OF SILICONES MEASURED AFTER IRRADIATION^{(a)(48)}

Silicone	Not irradiated			100 Megarads' Irradiation (2.1×10^5 Ergs $G^{-1}(C)$)			500 Megarads' Irradiation (4.5×10^5 Ergs $G^{-1}(C)$)		
	ϵ'	Tan δ	Resistivity, ohm-cm	ϵ'	Tan δ	Resistivity, ohm-cm	ϵ'	Tan δ	Resistivity, ohm-cm
<u>Elastomers</u>									
Dimethyl polysiloxane, 100 us	2.73	0.0001	1×10^{14}	2.72(b)	0.0001(c)	1×10^{14}	Gelled	Gelled	Gelled
Phenylmethyl polysiloxane	2.83	0.0002	2×10^{14}	2.81	0.01	5×10^{11}	2.86	0.05	5×10^{10}
<u>Resins</u>									
Silastic 30	2.9	0.001	1×10^{14}	3.3	0.001	1×10^{14}	2.2	0.005	1×10^{14}
Silastic 575	3.0	0.002	--	3.3	0.003	--	3.3	0.006	--
S-2048 Silastic	3.3	0.008	4×10^{13}	3.3	0.008	4×10^{13}	3.3	0.008	4×10^{13}
S-2007 Silastic	3.7	0.004	1×10^{14}	3.9	0.007	1×10^{14}	5.0	0.37	1×10^{14}
RTV Silastic	2.9	0.01	2×10^{13}	2.3	0.01	5×10^{13}	--	--	--
<u>Resins</u>									
Filled solventless resins	3.3	0.006	--	3.3	0.006	--	3.3	0.006	--
Molding compound	4.6	0.002	1×10^{14}	--	--	--	5.7	0.06	$8 \times 10^{11}(c)$

(a) Source: Dow Corning Corporation. All measurements at 23 C; complex permittivity data measured at 100.

(b) 50 megarads' irradiation (4.5×10^5 ergs $G^{-1}(C)$).(c) 1000 megarads' irradiation (9×10^6 ergs $G^{-1}(C)$).

TABLE A-25. DIELECTRIC PROPERTIES OF SILICONES DURING IRRADIATION (48)

Silicone	Not Irradiated		After 100 Mrads Irradiation (a)	
	ϵ'	$\tan \delta$	ϵ'	$\tan \delta$
<u>Fluids</u>				
Dimethyl polysiloxane, 100 cs	2.72	0.0015	2.76(b)	0.0015(b)
Phenylmethyl polysiloxane	2.76	0.0015	2.84	0.0025
<u>Elastomers</u>				
Silastic 80	2.99	0.002	3.06	0.015
Silastic-675	2.96	0.0025	3.01	0.025
S-2048 Silastic	3.21	0.0025	3.22	0.035
RTV 5513-14	2.80	0.004	2.80	0.035
<u>Neat-Glass System</u>				
Electrical-grade laminate	4.3	0.015	--	--
Low-pressure laminate	3.9	0.030	--	--

(a) Dose rate 0.1 megarads/hour.

(b) 4.5×10^9 ergs g^{-1} (CS) 50 megarads irradiation.

TABLE A-37. RESULTS OF PRELIMINARY IRRADIATION OF ELECTRICAL CABLE INSULATIONS⁽⁴⁹⁾

Cable Identification(a)	Rubber Insulation	Serviceability
Tested at 350 F for 185.5 Hours and 2.86×10^7 REP		
Springfield Wire & Tinsel Company		
(1)	Compound S-205	Poor-fair
Boston Insulated Wire & Cable Company		
(1)	BIW #20-71	Fair
(2)	SE-81686	Good
	SE-555 (jacket)	Poor
(3)	SE-81686	Good
	SE-555 (jacket)	Poor
(4)	SE-81686	Good
General Electric Company		
(1)	Waterford Compound 81427	Fair
(2)	Bridgeport Compound 1527	Good-excellent
(3)	SI 53917	Poor-fair
(4)	SI 53916	Poor-fair
(5)	SI 57420	Poor
(6)	SI 57421	Fair
Tested at 450 F for 69.3 Hours and 2.1×10^7 REP		
Boston Insulated Wire & Cable Company		
(4)	GE 81684	Good
General Electric Company		
(7)	Bridgeport Compound 1520-83	Good(b)

(a) Numbers refer to the correspondingly numbered item in Table A-38.

(b) 315 hr, 480 F, 4.5×10^6 r/hr, dynamically flexed six times/min. Did not fail under these conditions.

TABLE A-38. ELECTRICAL CABLES TESTED⁽⁴⁹⁾Springfield Wire & Tinsel Company

- (1) Single conductor, AWG No. 16 solid nickel-clad copper, insulated with S-205 silicone rubber, temperature 500-600 F, no metal shield; used as a control cable on nuclear reactors

Boston Insulated Wire & Cable Company

- (1) No. 20 AWG, single conductor, 1/32-inch compound BIW No. 20-71, with nickel-plated shield, temperature 500-600 F
- (2) No. 14 AWG, two conductor insulated with 1/64-inch SE 81686 and jacketed with G. E. SE-555, temperature 500-600 F
- (3) No. 14 AWG, same as (2) with nickel-plated shield
- (4) No. 16 AWG, four conductor with 1/64-inch SE 81686 with nickel-plated shield

General Electric Company

- (1) Single strand, single conductor insulated with Waterford Compound 81427, temperature 500-600 F
- (2) Single strand, single conductor insulated with Bridgeport Compound 1527, temperature 500-600 F.
- (3) No. 14 AWG, single conductor insulated with SI 53917 silicone with glass braid, temperature 500-600 F
- (4) No. 16 AWG, single conductor insulated with SI 53916 silicone rubber with glass braid, temperature 500-600 F
- (5) No. 18 AWG, silicone rubber SI 57420, asbestos, glass braid, temperature 380 F
- (6) No. 14 AWG, silicone rubber, SI 57421, asbestos, glass braid, and Teflon-tape insulation, temperature 750 F
- (7) No. 18 AWG, single conductor insulated with Bridgeport Compound 1520-83, temperature 400 F

TABLE A-10. COMPARISON OF MECHANICAL PROPERTIES OF SBR WIRE INSULATION AFTER IRRADIATION AT ROOM TEMPERATURE AND AT 158 F, AND AFTER HEAT AGING AT 158 F (11,51)

Time of Irradiation or Heat Aging ^(a) , days	Radiation Dose, ergs g ⁻¹ (C) x 10 ⁻⁹	Irradiated					
		Irradiated at RT		Irradiated at 158 F		Heat Aged at 158 F	
		Tested at RT	Tested at 158 F (b)	Tested at RT	Tested at 158 F	Tested at RT	Tested at 158 F
Tensile Strength, psi							
0	0	1060	770	1060	770	1060	770
1-1/2	0.84	--	--	960	680	--	--
3	1.68	--	--	970	660	--	--
3-1/3	--	--	--	--	--	--	--
3-3/4	2.1	970	780	--	--	950	750
6	3.36	--	--	--	--	--	--
7	--	--	--	940	670	--	--
7-1/2	4.2	920	750	--	--	1030	750
10-1/2	5.87	--	--	--	--	--	--
14	--	--	--	980	610	--	--
15	8.4	920	800	--	--	970	660
22-1/2	12.6	Broke	870	--	--	--	--
28	--	--	--	--	--	--	--
35	--	--	--	--	--	950	710
						950	950
Elongation, per cent							
0	0	290	300	290	300	290	300
1-1/2	0.84	--	--	300	280	--	--
3	1.68	--	--	180	180	--	--
3-1/3	--	--	--	--	--	--	--
3-3/4	2.1	250	220	--	--	270	270
6	3.36	--	--	--	--	--	--
7	--	--	--	200	200(c)	--	--
7-1/2	4.2	260	200	--	--	270	250
10-1/2	5.87	--	--	--	--	--	--
14	--	--	--	190	140	--	--
15	8.4	120	120	--	--	220	200
22-1/2	12.6	Broke	80	--	--	--	--
28	--	--	--	--	--	--	--
35	--	--	--	--	--	190	200
						160	160
Hardness, Shore A							
0	0	78	--	78	78	--	--
1-1/2	0.84	--	--	80	81	--	--
3	1.68	--	--	85	85	--	--
3-1/3	--	--	--	--	--	--	--
3-3/4	2.1	84	81	--	--	--	--
6	3.36	--	--	--	--	--	--
7	--	--	--	83	86	--	--
7-1/2	4.2	85	86	--	--	--	--
10-1/2	5.87	--	--	--	--	--	--
14	--	--	--	87	88	--	--
15	8.4	80	88	--	--	--	--
22-1/2	12.6	--	91	--	--	--	--
28	--	--	--	--	--	--	--
35	--	--	--	--	--	85	85
						85	85

TABLE A-39. (Continued)

Time of Irradiation or Heat Aging ^(a) , days	Radiation Dose, ergs g ⁻¹ (C) × 10 ⁻⁹	Irradiated					
		Irradiated at RT		Irradiated at 158 F		Heat Aged at 158 F	
		Tested at RT	Tested at 158 F (b)	Tested at RT	Tested at 158 F	Tested at RT	Tested at 158 F
		200 Per Cent Modulus, psi					
0	0	800	580	800	580	800	580
1-1/2	0.84	--	--	780	490	--	--
3	1.68	--	--	Broke	Broke	--	--
3-1/2	--	--	--	--	--	830	580
3-3/4	2.1	950	730	--	--	--	--
6	3.36	--	--	900(c)	670(d)	--	--
7	--	--	--	--	--	870	620
7-1/2	4.2	920	Broke	--	--	--	--
10-1/2	5.87	--	--	Broke	Broke	--	--
14	--	--	--	--	--	930	630
15	8.4	Broke	Broke	--	--	--	--
22-1/2	12.6	Broke	Broke	--	--	--	--
28	--	--	--	--	--	Broke	Broke

(a) Test values for the heat-aged samples are placed in their approximate relationship to the samples irradiated at 158 F based on the time of exposure to the elevated temperature. The time of irradiation was computed by dividing the exposure dose by the dose rate, 2.33×10^7 ergs g⁻¹(C) hr⁻¹, the radiation flux to which the samples were exposed at the Brookhaven National Laboratory Gamma Facility. With this compound, the samples irradiated at 158 F were subjected to a dose rate of 2.60×10^7 ergs g⁻¹(C) hr⁻¹. However, this higher dose rate was ignored for these calculations.

(b) The samples irradiated at room temperature and tested at 158 F were irradiated at the Materials Testing Reactor Gamma Facility. The radiation doses were slightly higher than those received by the samples irradiated at the Brookhaven National Laboratory Gamma Facility. Exposure doses at MTR were 0.22×10^9 , 3.4×10^9 , 5.2×10^9 , and 1.3×10^{10} ergs g⁻¹(C).

(c) Nine dumbbells tested.

(d) Three dumbbells tested.

TABLE A-10. COMPARISON OF MECHANICAL PROPERTIES OF NEOPRENE GHTSE TUBE STOCK AFTER IRRADIATION AT ROOM TEMPERATURE AND AT 158 F, AND AFTER HEAT AGING AT 158 F^{(1), (5)}

Time of Irradiation or Heat Aging(a), days	Radiation Dose ergs g ⁻¹ (C) × 10 ⁻⁹	Irradiated					
		Irradiated at RT		Irradiated at 158 F		Heat Aged at 158 F	
		Tested at RT	Tested at 158 F(b)	Tested at RT	Tested at 158 F	Tested at RT	Tested at 158 F
Tensile Strength, psi							
0	0	1830	1330	1830	1330	1310	1310
1-3/8	0.84	--	--	1860	1350	--	--
2-3/4	1.68	--	--	1740	1290	--	--
3-1/2	2.1	1820	1370(c)	--	--	--	--
5-1/2	3.36	--	--	1910	1230	--	--
7	4.2	1860	1350	--	--	--	--
9-2/3	5.87	--	--	2080	1260	--	--
14	8.4	2150	1460	--	--	--	--
21	12.6	Broke	1470	--	--	--	--
40	--	--	--	--	--	2010	1380
150	--	--	--	--	--	2030	1550
Elongation, per cent							
0	0	390	320	390	320	390	320
1-3/8	0.84	--	--	300	250	--	--
2-3/4	1.68	--	--	260	200	--	--
3-1/2	2.1	250	130	--	--	--	--
5-1/2	3.36	--	--	180	140	--	--
7	4.2	180	100	--	--	--	--
9-2/3	5.87	--	--	110	90	--	--
14	8.4	100	40	--	--	--	--
21	12.6	Broke	30	--	--	--	--
40	--	--	--	--	--	250	180
150	--	--	--	--	--	210	170
Hardness, Shore A							
0	0	73	--	73	73	73	73
1-3/8	0.84	--	--	73	73	--	--
2-3/4	1.68	--	--	73	73	--	--
3-1/2	2.1	78	84	--	--	--	--
5-1/2	3.36	--	--	75	--	--	--
7	4.2	80	84	--	--	--	--
9-2/3	5.87	85	--	85	--	--	--
14	8.4	--	91	--	--	--	--
21	12.6	--	99	--	--	--	--
40	--	--	--	--	--	80	--
150	--	--	--	--	--	84	--

TABLE A-40. (Continued)

Time of Irradiation or Heat Aging ^(a) , days	Radiation Dose, ergs g ⁻¹ (C) × 10 ⁻⁹	Irradiated					
		Irradiated at RT		Irradiated at 158 F		Heat Aged at 158 F	
		Tested at RT	Tested at 158 F ^(b)	Tested at RT	Tested at 158 F	Tested at RT	Tested at 158 F
		200 Per Cent Modulus, psi					
0	0	1340	930	1340	930	1340	930
1-3/8	0.84	--	--	1630	1210	--	--
2-3/4	1.68	--	--	1620	1270	--	--
3-1/2	2.1	1650	Broke	--	--	--	--
5-1/2	3.36	--	--	Broke	Broke	--	--
7	4.2	Broke	Broke	--	--	--	--
9-2/3	5.87	--	--	Broke	Broke	--	--
14	8.4	Broke	Broke	--	--	--	--
21	12.6	Broke	Broke	--	--	--	--
50	--	--	--	--	--	1950	Broke
150	--	--	--	--	--	2030(c)	Broke

- (a) Test values for the heat-aged samples are placed in their approximate relationship to the samples irradiated at 158 F based on the time of exposure to the elevated temperature. The time of irradiation was computed by dividing the exposure dose by the dose rate, 2.52×10^7 ergs g⁻¹(C) hr⁻¹, the radiation flux to which the samples were exposed at the Brookhaven National Laboratory Gamma Facility.
- (b) The samples irradiated at room temperature and tested at 158 F were irradiated at the Materials Testing Reactor Gamma Facility. The radiation doses were slightly higher than those received by the samples irradiated at the Brookhaven National Laboratory Gamma Facility. Exposure doses at MTR were 0, 2.2×10^9 , 4.4×10^9 , 8.9×10^9 , and 1.3×10^{10} ergs g⁻¹(C).
- (c) Four dumbbells tested.

TABLE A-42. EFFECTS OF NUCLEAR RADIATION ON THE PHYSICAL, MECHANICAL, AND ELECTRICAL PROPERTIES OF A TAC-POLYESTER AND A SILICONE LAMINATE ⁽⁷¹⁾

Type of Test	$\frac{\text{Irradiated}}{\text{Nonirradiated}} \times 100$					
	R. T.	L-4232 TAC-Polyester		R. T.	DC-2108 Silicone	
		450 F/1/2 Hr	500 F/100 Hr		450 F/1/2 Hr	500 F/100 Hr
Tension stress (90° warp)	94.3	94.0	111.0	101.0	97.0	92.2
Primary modulus	101.3	93.0	121.0	98.3	102.0	92.6
Secondary modulus	108.6	104.0	119.0	97.1	96.6	96.7
Compression stress (90° warp)	91.6	149.0	114.1	96.6	94.0	89.6
Primary modulus	113.0	100.0	89.2	100.0	92.2	90.6
Flexure stress (90° warp)	119.2	140.0	110.2	80.0	74.0	100.0
Primary modulus	100.2	110.0	110.0	93.4	92.8	101.0
Interlaminar shear strength (90° warp)	74.3	94.0	72.0	78.2	79.0	77.1
Impact strength	83.4	--	--	131.0	--	--
Specific gravity	100.0	--	--	100.0	--	--
Resin content	100.0	--	--	100.0	--	--
Molecular constant	102.6	--	--	101.0	--	--
Loss tangent	83.4	--	--	69.5	--	--

Note: Exposure dose was 1.7×10^5 crg g^{-1} (C) (2×10^7 roentgens and 3.5×10^{14} eV/g).

TABLE A-41. COMPARISON OF PRE- AND POSTIRRADIATION MECHANICAL PROPERTIES OF 12 TYPES OF LAMINATES ^(1,2)

Description of Laminate	Flux(a)	Ultimate Tensile Strength, psi x 10 ⁻³	Modulus of Elasticity, psi x 10 ⁻⁶	Ultimate Compressive Strength, psi x 10 ⁻³	Notch Impact lb in. -1	Specific Gravity	Resin Content, per cent
Phenolic resin (Conolon 506) and glass fabric	Control	52.2	3.57	54.0	195	1.98	23.5
	1	51.4	3.16	54.00	178	1.79	22.4
	2	51.5	3.17	63.7	166	1.96	21.0
	3	45.5	3.03	65.0	183	1.97	22.9
	4	52.6	3.11	65.0	180	1.97	22.0
Phenolic resin (Conolon 506) and asbestos fabric	Control	11.9	1.26	16.9	34	1.54	62.7
	1	12.0	1.13	17.0	32	1.57	60.8
	2	12.4	1.16	16.5	32	1.56	64.4
	3	12.6	1.11	16.2	31	1.58	60.0
	4	11.3	1.09	16.9	29	1.55	61.8
Phenolic resin (F120-19) and glass fabric	Control	43.2	3.03	62.9	115	1.85	21.7
	1	38.8	3.11	60.9	2.5	1.92	21.5
	2	51.7	3.20	61.7	220	1.78	21.5
	3	46.5	3.04	52.9	213	1.91	26.2
	4	55.3	3.00	59.6	230	1.94	21.0
Phenolic resin (F120-19) and asbestos fabric	Control	19.1	1.41	13.9	49	1.66	56.9
	1	17.9	1.42	14.5	57	1.61	51.0
	2	19.2	1.15	14.4	51	1.65	54.0
	3	18.6	1.13	14.3	42	1.60	54.6
	4	18.2	1.16	14.0	51	1.63	54.4
Phenolic resin (Mokhtoy AH-81) and asbestos fabric	Control	20.7	3.16	27.7	60	2.00	20.2
	1	20.8	3.16	31.0	60	2.01	19.5
	2	20.6	3.13	27.6	56	1.94	19.2
	3	20.6	3.21	25.4	60	1.97	19.5
	4	20.8	3.19	29.1	56	1.99	20.0
Phenolic resin (Mokhtoy AH-81) and glass fabric	Control	10.7	1.17	9.1	17	1.51	95.8
	1	11.1	1.17	8.5	15	1.54	94.5
	2	11.0	1.18	9.8	18	1.48	96.3
	3	11.2	1.22	6.4	18	1.49	96.3
	4	12.2	1.08	8.7	16	1.68	91.9
Epoxy resin (Epon 828) and glass fabric	Control	53.5	2.83	60.3	203	1.95	27.5
	1	52.1	2.92	61.4	188	1.95	31.6
	2	54.4	2.87	63.2	197	1.94	26.0
	3	54.9	2.89	60.6	177	1.95	26.5
	4	54.9	2.76	61.3	196	1.89	29.3
Epoxy resin (Epon 828) and asbestos fabric	Control	24.8	1.66		41	1.62	53.8
	1	25.4	1.74	16.3	45	1.62	51.0
	2	26.0	1.70	16.8	44	1.64	50.2
	3	24.9	1.70	17.1	37	1.64	54.2
	4	23.0	1.67	17.0	19	1.61	53.5
Epoxy resin (Epon X-131) and glass fabric	Control	19.3	2.44	50.8	69	1.85	34.7
	1	20.5	2.39	52.8	74	1.67	31
	2	20.4	2.36	52.1	69	1.87	31.3
	3	19.9	2.42	52.8	82	1.89	32.4
	4	21.3	2.55	54.8	84	1.89	33.5
Epoxy resin (Epon X-131) and asbestos fabric	Control	25.4	1.91	21.1	32	1.65	59.6
	1	25.7	1.88	21.5	35	1.65	60.1
	2	26.9	1.93	21.6	36	1.66	60.1
	3	26.7	1.89	21.1	38	1.66	59.8
	4						

TABLE A-43. (Continued)

Description of Laminate	Flux (a)	Ultimate Tensile Strength, psi $\times 10^{-3}$	Modulus of Elasticity, psi $\times 10^{-6}$	Ultimate Compressive Strength, psi $\times 10^{-3}$	Notch Impact, lb in. $^{-1}$	Specific Gravity	Resin Content, per cent
Polyester resin (American Cyanamid 4232) and glass fabric	Control	48.2	2.93	27.6	289	2.04	29.9
	1	48.7	3.05	26.7	241	2.02	30.2
	2	49.5	2.88	30.6	281	2.02	30.4
	3	50.6	2.85	28.0	270	2.00	31.6
	4	50.2	2.98	28.0	287	2.03	30.4
Polyester resin (American Cyanamid 4232) and asbestos fabric	Control	19.6	1.55	20.6	41	1.69	64.2
	1	18.5	1.58	20.0	46	1.72	60.4
	2	18.9	1.48	20.7	45	1.69	60.7
	3	18.9	1.53	20.0	41	1.70	65.3
	4	20.0	1.62	21.2	40	1.70	63.3
(a)	Flux	Gamma Dose, ergs cm^{-2} (C)		Integrated Fast-Neutron Flux, n cm^{-2} ($E > 2.9$ Mev)			
	1	9.3×10^6		1.2×10^{12}			
	2	9.3×10^7		1.2×10^{13}			
	3	9.3×10^8		1.2×10^{14}			
	4	9.3×10^9		1.2×10^{15}			

All radiation was at uncontrolled ambient temperature estimated to be between 70 and 80 F for the three lower fluxes and approximately 160 F for Flux 4. Testing was at room temperature.

TABLE A-44. AVERAGE COMPRESSIVE STRENGTHS FOR
TWO TYPES OF HONEYCOMB-CORE TEST
SPECIMENS ⁽⁷⁴⁾

Flux Group(a)	Average Compressive Strength of Glass-Fiber-Reinforced Material, psi	
	Hexcel 91LD	Hexcel F-120
Controls	348	1253
1	2236	1102
2	2458	1256
3	2436	1292
4	2417	1267

(a)	Gamma Dose, Mrad $\times 10^3$ (c)	Integrated Fast-Neutron Flux, $n \text{ cm}^{-2}$ ($E > 2.0 \text{ Mev}$)
1	9.3×10^6	1.2×10^{12}
2	9.3×10^7	1.2×10^{13}
3	9.3×10^8	1.2×10^{14}
4	9.3×10^9	1.2×10^{15}

TABLE A-45. EFFECTS OF RADIATION ON LAMINATED SILICONES (80)

Material	Properties	Control	Irradiated	
			2.5×10^7 Ergs G^{-1}	(C)
Dacron Laminated With DC-X-6015A Silicone	Cut Strip Tensile Strength, lb/inch	84		83
	Tongue Tear Resistance, lb	11.9		12.4
	Water Absorption, % increase in weight	9.38		8.25
Orlon Laminated With DC-X-6015A Silicone	Cut Strip Tensile Strength, lb/inch	81		75
	Tongue Tear Resistance, lb	4.7		2.7
	Water Absorption, % increase in weight	9.16		7.64
Glass Cloth Laminated With Silicone, post-formable sheet (MIL-p-997)	Ultimate Tensile Strength, psi	28,118		26,046
	Ultimate Compressive Strength, psi	15,412		14,044
	Water Absorption, % increase in weight	9.37		0.12
	Barcol Hardness	59		58
	Specific Gravity at 25 C	1.69		1.68
	Coefficient of Thermal Expansion, 10^{-5} inch/inch	0.62		0.54
	Dielectric Strength, volts/mil	83.0		71.1
	Surface Resistivity, 10^6 ohms	17.8		17.8
	Volume Resistivity, 10^6 ohm-inch	23.6		23.6
	Arc Resistance, ohms	244.7		246.3

TABLE A-46. RECIPE FOR NATURAL RUBBER (a) WITH SHORE A DUROMETER HARDNESS OF 35 TO 40 (35)

Trade Name	Composition	Use	Parts Per Hundred Sheet
Smoke Sheet PEF Black	Natural gum stock rubber Fast extrusion-sulfate black, fine-grain carbon	Base stock Filler	100 35
P-33 Black	Large-grain "thermal black" carbon	Filler	8
Dixie Clay	Kaolin $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$	Filler	5
ZnO No. 169	Zinc oxide	Accelerator	5
Stearic Acid	Pure chemical	Plasticizer, processing aid	1
Agente Resin D	Polymerized trimethyldihydroquinoline	Antioxidant	1
Flexamine	A mixture of 65 per cent of a diarylamine ketone and 35 per cent N, N diphenyl paraphenylenediamine	Antioxidant	1
Paralube	Petroleum lubricant	Lubricating agent	5
Sulfur	Pure chemical	Curing agent	1.5
Tellor	Metallic tellurium	Activator	0.05
Methyl Tuads	Tetramethylethiuram disulfide	Accelerator	0.05
Zincate	Zinc dimethyl diisocarbamate	A secondary accelerator to make Tuads reactive	0.05
Pepton 22	Diortho-benzamidothiuram disulfide	Plasticizer	0.02

(a) Rubber supplied by Immel Engineering and Development Company.

TABLE A-47. EFFECTS OF IRRADIATION ON MECHANICAL PROPERTIES OF STRESSED AND UNSTRESSED NATURAL RUBBER O-RINGS (85)

Specimen ^(a)	Exposure ^(b)	Hardness Change ^(c) , per cent	Stress Condition ^(d)	Permanent Set ^(e) , per cent		Tensile Strength, psi	Ultimate Elongation, per cent	Modulus of Elasticity, psi						
				A	B			100%	200%	300%	400%	500%		
Control 1	0		Failed in testing machine											
2	0	0	Stressed	6	0	1070	520	100	230	250	620	1050		
3	0	--	Unstressed	--	0	1180	550	160	250	440	820	1180		
4	0	--	Unstressed	--	--	1130	550	160	230	410	730	1110		
5	0	--	Unstressed	--	--	1450	550	140	340	630	930	1250		
6	0	--	Unstressed	--	--	1220	450	160	330	630	1020	--		
7	0	--	Unstressed	--	--	1120	540	110	290	560	860	1120		
Mean						1230	530	146	288	534	872	1174		
Irradiated 1	1	0	Unstressed	--	(Specimens 3-7)	1170	420	200	320	750	1160	--		
3	2	+31	Unstressed	--	--	1170	320	250	730	1160	--	--		
5	3	+45	Unstressed	--	--	940	220	360	840	--	--	--		
2	1	+5	Stressed	17	29	1250	420	140	330	650	1130	--		
4	2	+33	Stressed	87	100	450	200	250	450	--	--	--		
6	3	+47	Stressed	80	100	450	190	250	--	--	--	--		

(a) Specimens were cut in 6-inch lengths from two O-rings and randomly distributed.

(b)

Dose for Indicated Exposure

1 2 3

Integrated Fast-Neutron

Flux, $n\text{ cm}^{-2}(\geq 2.9\text{ Mev})$ 5.2 x 10¹³ 2.7 x 10¹⁴ 5.3 x 10¹⁴

Integrated Thermal-Neutron

Flux, $n\text{Vot}(\geq 0.48\text{ ev})$ 2.1 x 10¹⁴ 8.4 x 10¹⁴ 1.7 x 10¹⁵

Integrated Gamma Flux,

ergs $\text{g}^{-1}(\text{C})$ 6.0 x 10⁸ 3.0 x 10⁹ 6.0 x 10⁹Total Dose, ergs $\text{g}^{-1}(\text{C})$ 6.4 x 10⁸ 3.2 x 10⁹ 6.3 x 10⁹

(c) Mean hardness prior to irradiation was Shore A Durometer 36.

(d) Stressed condition during irradiation: 25 per cent compression, 180° bend with 5/8-inch radius (includes Specimens 2, 4, and 6, irradiated, and Specimen 2, unirradiated control).

(e) Permanent Set A: Per cent compression set, 1 week after release from 25 per cent compression.

Permanent Set B: Per cent set in flexure, 1 week after release from 180° bend.

TABLE A-48. EFFECTS OF IRRADIATION ON HARDNESS AND COMPRESSION SET OF UNSTRESSED NATURAL RUBBER BUTTONS⁽⁸⁵⁾

Specimen	Exposure(a)	Hardness			Significance	Compression Set(b)		
		Shore A Durometer	Mean 195 Per Cent Confidence Interval)	Change, per cent		Per Cent Mean (95 Per Cent Confidence Interval)	Significance	
Control	1	0	38			14.1		
	2	0	38			7.5	Reject	
	3	0	40			10.1		
	4	0	40			12.0		
	5	0	38			11.3		
	6	0	38			13.6	12.7 ± 2.0	
Irradiated	1	38				9.0		
	1	39				7.9		
	1	37				10.5		
	1	38				7.7		
	1	36	38 ± 1	-3	NS	10.1	9.5 ± 1.4	S
	2	47				3.7		
	2	45				3.7		
	2	(c)						
	2	44				6.7		
	2	44	45 ± 2	+15	S	5.6	6.0 ± 2.0	S
	3	(c)						
	3	46				3.6		
	3	48				7.6		
	3	53				3.6		
	3	48	49 ± 5	+26	S	6.7	5.7 ± 2.9	S

(a)

	Dose for Indicated Exposure		
	1	2	3
Integrated Fast-Neutron Flux, n cm ⁻² (E > 2.9 Mev)	5.2 × 10 ¹³	2.7 × 10 ¹⁴	5.3 × 10 ¹⁴
Integrated Thermal-Neutron Flux, nv ₀ l (E > 0.48 ev)	2.1 × 10 ¹⁴	8.4 × 10 ¹⁴	1.7 × 10 ¹⁵
Integrated Gamma Flux, ergs g ⁻¹ (C)	6.0 × 10 ⁸	3.0 × 10 ⁹	6.0 × 10 ⁹
Total Dose, ergs g ⁻¹ (C)	6.4 × 10 ⁸	3.2 × 10 ⁹	6.3 × 10 ⁹

(b) Compression set measured after irradiation of unstressed buttons Method ASTM-D-395-55 (constant deflection)

$$\frac{t_1 - t_2}{t_1 - t_3} \times 100 = \text{per cent set,}$$

where

t₁ = original thicknesst₂ = thickness after compression 24 hours at room temperaturet₃ = thickness during compression (0.300 inch).

(c) Specimens cracked excessively; could not be tested.

TABLE A-49. EFFECTS OF HEAT AGING ON VITON A O-RINGS (13)
 Tested at Room Temperature to 600 F in 12 Psig Air

Groove Type	O-Ring Width Before Test, in.	Per Cent Squeeze	O-Ring Width After Test, in.	Compression Set, per cent of original thickness	Time at 600 F, hours	Remarks
5° taper	0.199	8.4	0.169 avg	15.1	12	Sealed up to 600 F; failed at 500 F upon cooling
10° taper	0.198	12.6	0.150 avg	24.3	12	Sealed up to 600 F; failed at 500 F upon cooling
15° taper	0.201	17.8	0.147 avg	25.7	12	Sealed up to 600 F; failed at 500 F upon cooling
Rectangular	0.200	26.5	0.140	30	12	Sealed to 600 F; failed at 600 F
Vee	0.200	7.5	--	--	12	Sealed to 600 F; failed at 600 F
5° taper	0.200	8.2	0.171 avg	14.9	12	Sealed at 600 F; failed at 600 F
Rectangular	0.200	26.5	0.140	25.5	2	Sealed at 600 F; failed at 600 F
15° taper	0.200	17.7	0.146 avg	25.4	2	Sealed at 130 F; failed at 600 F
Rectangular	0.200	26.5	0.149	25.2	2	Sealed at 600 F; failed at 200 F
5° taper	0.200	8.4	0.173 avg	13.5	2	Did not fail
Vee	0.200	6.1	--	--	2	Sealed at 600 F; failed at 250 F
					2	Sealed at 600 F; failed at 300 F

TABLE A-50. TENSILE STRENGTH AND ELONGATION OF SEALANT SPECIMENS IRRADIATED IN AIR⁽¹⁷⁾

Material	Dose		Approximate Air Temperature, F	Average Tensile Strength, psi	Average Elongation, per cent
	Gamma, ergs g ⁻¹ (C)	Neutron, n cm ⁻² (E > 0.33 Mev)			
PR-1422	Control	Control	--	389 ± 28	228 ± 21
	1 × 10 ⁹	1.4 × 10 ¹⁵	90	338 ± 18	177 ± 12
	7 × 10 ⁹	8 × 10 ¹⁵	99	290 ± 21	88 ± 10
EC-1010	Control	Control	--	129 ± 17	130 ± 17
	1 × 10 ⁹	1.3 × 10 ¹⁵	90	180 ± 18	128 ± 20
	7 × 10 ⁹	8 × 10 ¹⁵	90	144 ± 28	60 ± 13
EC-1620	Control	Control	--	125 ± 8	110 ± 11
	1.2 × 10 ⁹	1.4 × 10 ¹⁵	90	163 ± 22	123 ± 22
	7 × 10 ⁹	8 × 10 ¹⁵	90	140 ± 24	70 ± 27

TABLE A-51. TENSILE STRENGTH AND ELONGATION OF SEALANT SPECIMENS IRRADIATED IN FUEL⁽¹⁷⁾

Material	Dose		Immersion Time Before Irradiation, days	Immersion Time After Irradiation, days	Average Tensile Strength, psi	Average Elongation, per cent
	Gamma, ergs g ⁻¹ (C)	Neutron, n cm ⁻² (E > 0.33 Mev)				
PR-1422	Control	Control	--	30	360 ± 18	173 ± 15
	3 × 10 ⁹	1.8 × 10 ¹⁵	7	120	237 ± 18	159 ± 18
	7 × 10 ⁹	6 × 10 ¹⁵	7	30	86 ± 23	40 ± 7
EC-1010	Control	Control	--	30	132 ± 14	120 ± 28
	2 × 10 ⁹	1.8 × 10 ¹⁵	7	120	74 ± 10	80 ± 33
	7.5 × 10 ⁹	7 × 10 ¹⁵	7	30	29 ± 9	35 ± 21
EC-1620	Control	Control	--	30	127 ± 18	146 ± 22
	2 × 10 ⁹	1.6 × 10 ¹⁵	7	120	92 ± 17	115 ± 27
	7.5 × 10 ⁹	7 × 10 ¹⁵	7	30	33 ± 18	37 ± 15

TABLE A-52. PEEL STRENGTH OF SEALANT SPECIMENS IRRADIATED IN AIR⁽¹⁷⁾

Material	Dose		Approximate Air Temperature, F	Average Peel Strength, lb in. ⁻¹	Average Cohesive Strength, per cent
	Gamma, ergs g ⁻¹ (G)	Neutron, n cm ⁻² (E > 0.33 Mev)			
PR-1422	Control	Control	--	43	100
	1.5 x 10 ⁹	1.5 x 10 ¹⁵	90	42	100
	7 x 10 ⁸	1.2 x 10 ¹⁵	90	41	100
	1.5 x 10 ⁹	2 x 10 ¹⁵	90	48	100
	6.5 x 10 ⁸	1.1 x 10 ¹⁵	90	44	100
	1.5 x 10 ¹⁰	1.2 x 10 ¹⁶	90	6	100
	2 x 10 ¹⁰	1.5 x 10 ¹⁶	90	6	100
	1.4 x 10 ¹⁰	1.2 x 10 ¹⁶	90	7	100
	1.5 x 10 ¹⁰	1.2 x 10 ¹⁶	90	6	100
EC-1610	Control	Control	--	26	100
	6 x 10 ⁸	9 x 10 ¹⁴	90	14	100
	1 x 10 ⁹	9 x 10 ¹⁴	90	25	100
	1 x 10 ⁹	9 x 10 ¹⁴	90	26	100
	1 x 10 ⁹	1 x 10 ¹⁵	90	14	100
	1.5 x 10 ¹⁰	1.2 x 10 ¹⁶	90	5	100
	1 x 10 ¹⁰	9 x 10 ¹⁵	90	4	100
	1.5 x 10 ¹⁰	1.3 x 10 ¹⁶	90	4	100
	2.5 x 10 ¹⁰	1.5 x 10 ¹⁶	90	2	100

TABLE A-53. PEEL STRENGTH OF SEALANT SPECIMENS IRRADIATED IN FUEL ⁽¹⁷⁾

Material	Dose		Immersion Time Before Irradiation, days	Immersion Time After Irradiation, days	Average Peel Strength, lb in. ⁻¹	Average Cohesive Strength, per cent
	Gamma, ergs g ⁻¹ (C)	Neutron, n cm ⁻² (E > 0.33 Mev)				
PR-1420	Control	Control	--	30	43	100
	3 x 10 ⁹	1.6 x 10 ¹⁶	7	30	27	100
	1.2 x 10 ¹⁰	9 x 10 ¹⁵	7	30	8	100
EC-1010	Control	Control	--	30	18	100
	2.6 x 10 ⁹	1.4 x 10 ¹⁶	7	30	21	100
	1.2 x 10 ¹⁰	9 x 10 ¹⁵	7	30	3	100

TABLE A-54. COHESIVE STRENGTH OF SEALANT SPECIMENS IRRADIATED IN AIR ⁽¹⁷⁾

Material	Dose		Approximate Air Temperature, F	Average Cohesive Strength, psi	Type of Failure	
	Gamma, ergs g ⁻¹ (C)	Neutron, n cm ⁻² (E > 0.33 Mev)			Average Adhesive Strength, per cent	Average Cohesive Strength, per cent
EC-1520	Control	Control	--	177 ± 32	0	100
	2.4 x 10 ⁹	1 x 10 ¹⁵	90	178 ± 22	0	100
	1 x 10 ¹⁰	1 x 10 ¹⁶	90	154 ± 10	0	100

TABLE A-55. COMPRESSION SET AND SOFTNESS OF VULCANIZATES AFTER EXPOSURE TO 10^8 ROENTGENS (39)

Rubber	Curing System	Antioxidant	High Resonant Energy Ingredient	Comp. Set %	Softness Indent. mm
Natural	Thionex (1) - sulfur			80	39
Natural	Thionex-sulfur	Neozone D (2)		73	50
Synpol 1000	Thionex-sulfur			83	31
Synpol 1000	Thionex-sulfur	Neozone D		71	48
Naugapol 1023	Thionex-sulfur			86	36
Naugapol 1023	Thionex-sulfur	Neozone D		79	60
Synpol 1500	Thionex-sulfur			75	43
Synpol 1500	Thionex-sulfur	Neozone D		64	59
Synpol 1500	Thionex-sulfur	Santoflex GP (3)		65	64
Synpol 1500	Thionex-sulfur	Thermoflex A (4)		59	60
Synpol 1500	Thionex-sulfur	Thermoflex A	Dibenzyl phthalate	49	64
Synpol 1500	Thionex-sulfur		Acridine	54	68
Synpol 1500	DICup 400 (5)			69	48
Naugapol 1504	Thionex-sulfur			85	48
Naugapol 1504	Thionex-sulfur	Neozone D		71	46
Hycar 2001	Thionex-sulfur			81	40
Hycar 2001	Thionex-sulfur	Neozone D		73	52
Hycar 1001	Thionex-sulfur			83	28
Hycar 1001	Thionex-sulfur	Neozone D		77	40
Hycar 1002	Thionex-sulfur			84	27
Hycar 1002	Thionex-sulfur	Neozone D		78	38
Hycar 1014	Thionex-sulfur			80	25
Hycar 1014	Thionex-sulfur	Neozone D		85	42
Hycar 1041	Thionex-sulfur			88	26
Hycar 1041	Thionex-sulfur	Neozone D		82	41
Hycar 1041	Thionex-sulfur	Neozone D	Santizer 160 (6)	66	58

TABLE A-55. (Continued)

Rubber	Curing System	Antioxidant	High Resonant Energy Ingredient	Comp. Set %	Softness Indent. mm
Hycar 1041	Thionex-sulfur	Age Rite Hidar (7)		69	52
Hycar 1041	DiCup 40C			91	31
Hycar 1042	Thionex-sulfur			83	27
Hycar 1042	Thionex-sulfur	Neozone D		74	41
Hycar 1043	Thionex-sulfur			85	32
Hycar 1043	Thionex-sulfur	Neozone D		74	51
Hycar 1071	Thionex-sulfur			79	22
Hycar 1071	Thionex-sulfur	Neozone D		71	43
Hycar 1072	Thionex-sulfur			79	21
Hycar 1072	Thionex-sulfur	Neozone D		67	16
Hycar 1072	Thionex-sulfur	Wingstay 100 (8)		58	40
Phlprene VP-25	Ethyl Tundr (9)-Sul- famid R (10) p-xylyne hexachloride			77	12
Neoprene WRT	Thiata B (11)			87	18
Neoprene WRT	Thiata B	Neozone A (12)		74	38
Viton A-HV	HMDA carbamate (13) Zinc oxide-Dyphos (14)			100	23
Gentane S	DiCup 40C			81	103
Adiprene C	DiCup 40C			65*	54
Adiprene C	DiCup 40C		Santelizer 160	56*	67
Hycar 4021	Triethylene tetramine			30	48
Silicone W96	Tertiary butyl peroxide			98	22
Silastic S2048	Not known			97	30
Silastic LS-53	Not known			103	49

Footnotes appear on the following page.

Footnotes for Table A-55

- Some of the specimens were crushed during the period of compression. This indicated that the ultimate elongation of the vulcanizate was marginal.

- | | |
|-----------------------------------------------|-----------------------------------------------|
| (1) Tetramethyl thiram monosulfide | (8) Composition not disclosed by manufacturer |
| (2) N-phenyl-beta-naphthylamine | (9) Tetraethyl thiram disulfide |
| (3) N-cyclohexyl-N'-phenyl-p-phenylenediamine | (10) 4,4'-dithio dimorpholine |
| (4) 50% N-phenyl-beta-naphthylamine | (11) "Trialkyl" thiourea |
| 25% 4,4'-dimethoxydiphenylamine | (12) N-phenyl-alpha-naphthylamine |
| 25% N,N'-diphenyl-para-phenylenediamine | (13) Hexamethylene diamine carbamate |
| (5) 40% dicumyl peroxide, 60% inert filler | (14) Dibasic lead phosphite. |
| (6) Butyl benzyl phthalate | |
| (7) 50% p-isopropoxy diphenylamine | |
| 50% diphenyl-p-phenylenediamine | |

TABLE A-56. COMPARISON OF MECHANICAL PROPERTIES OF NEOPRENE PACKING COMPOUND⁽¹⁾ AFTER IRRADIATION AT ROOM TEMPERATURE AND AT 158 F, AND AFTER HEAT AGING AT 158 F⁽⁵¹⁾

Time of Irradiation or Heat Aging(b), days	Radiation Dose, ergs g ⁻¹ (C) x 10 ⁻⁹	Irradiated					
		Irradiated at RT		Irradiated at 158 F		Heat Aged at 158 F	
		Tested at RT	Tested at 158 F(c)	Tested at RT	Tested at 158 F	Tested at RT	Tested at 158 F
Tensile Strength, psi							
0	0	2130	400	2130	400	2130	400
1-3/8	0.84	--	--	1470	240(d)	--	--
2-3/4	1.68	--	--	600	250(d)	--	--
3-1/3	--	--	--	--	--	--	270
3-1/2	2.1	740	260	--	--	--	--
5-1/2	3.36	--	--	350	120(d)	--	--
7	4.2	300	250	--	--	--	--
9-2/3	5.87	--	--	310	140(d)	--	--
14	8.4	350	310	--	--	--	300
21	12.6	Broke	310	--	--	--	--
28	--	--	--	--	--	1880	--
56	--	--	--	--	--	1910	130
70	--	--	--	--	--	1940	--
Elongation, per cent							
0	0	760	340	760	340	760	340
1-3/8	0.84	--	--	470	210(d)	--	--
2-3/4	1.68	--	--	290	170(d)	--	--
3-1/3	--	--	--	--	--	--	270
3-1/2	2.1	270	80	--	--	--	--
5-1/2	3.36	--	--	130	120(d)	--	--
7	4.2	100	60	--	--	--	--
9-2/3	5.87	--	--	80	60(d)	--	--
14	8.4	40	10	--	--	--	260
21	12.6	Broke	20	--	--	--	--
28	--	--	--	--	--	650	--
56	--	--	--	--	--	650	270
70	--	--	--	--	--	660	--
Hardness, Shore A ₁							
0	0	45	45	45	45	45	45
1-3/8	0.84	--	--	45	48	--	--
2-3/4	1.68	--	--	55	52	--	--
3-1/3	--	--	--	--	--	--	--
3-1/2	2.1	51	50	--	--	--	--
5-1/2	3.36	--	--	60	60	--	--
7	4.2	62	64	--	--	--	--
9-2/3	5.87	--	--	62	65	--	--
14	8.4	75	74	--	--	--	--
21	12.6	--	78	--	--	--	--
28	--	--	--	--	--	47	--
56	--	--	--	--	--	47	--
70	--	--	--	--	--	48	--

TABLE A-56. (Continued)

Time of Irradiation or Heat Aging ^(b) , days	Radiation Dose, ergs g ⁻¹ (C) x 10 ⁻⁹	Irradiated					
		Irradiated at RT		Irradiated at 158 F		Heat Aged at 158 F	
		Tested at RT	Tested at 158 F ^(c)	Tested at RT	Tested at 158 F	Tested at RT	Tested at 158 F
		200 Per Cent Modulus, psi					
0	0	209	170	200	170	200	170
1-3/8	0.84	--	--	270	Broke	--	--
2-3/4	1.68	--	--	300	Broke	--	--
3-1/2	--	--	--	--	--	--	200
3-1/2	2.1	429	Broke	--	--	--	--
5-1/2	3.36	--	--	Broke	Broke	--	--
7	4.2	Broke	Broke	--	--	--	--
9-2/3	5.87	--	--	Broke	Broke	--	--
14	8.4	Broke	Broke	--	--	--	240
21	12.6	Broke	Broke	--	--	--	--
28	--	--	--	--	--	130	--
56	--	--	--	--	--	210	230
70	--	--	--	--	--	230	--

(a) Neoprene W; Neoprene WHV, 60:40.

(b) Test values for the heat-aged samples are placed in their approximate relation ship to the samples irradiated at 158 F based on the time of exposure to the elevated temperature. The time of irradiation was computed by dividing the exposure dose by the dose rate, 2.52×10^7 ergs g⁻¹ (C) hr⁻¹, the radiation flux to which the samples were exposed at the Brookhaven National Laboratory Gamma Facility.

(c) The samples irradiated at room temperature and tested at 158 F were irradiated at the Materials Testing Reactor Gamma Facility. The radiation doses were slightly higher than those received by the samples irradiated at the Brookhaven National Laboratory Gamma Facility. Exposure doses at MTR were 0, 2.7×10^9 , 4.8×10^9 , 8.9×10^9 , and 1.3×10^{10} ergs g⁻¹ (C).

(d) Four dumbbells tested.

TABLE A-57. EFFECTS OF IRRADIATION ON COPOLYMERS OF METHYL METHACRYLATE⁽¹¹⁰⁾

Comonomer	Per Cent Comonomer	Maximum Radiation Dose		Effects
		Krgs C ⁻¹ (C)	Megaröntgens	
Ethyl methacrylate	50	8.8×10^8	10	None
	100	8.8×10^8	10	Degradation
Octyl methacrylate	10	8.8×10^8	10	Degradation
	50	8.8×10^8	10	Degradation
Methyl acrylate	10	4.7×10^9	54	Degradation
	50	8.8×10^9	100	Increased molecular weight; soft
	90	8.8×10^9	100	Insoluble (0); soft
	100	6.6×10^9	75	Insoluble; soft
Isobutyl acrylate	10	6.8×10^8	10	Degradation
	50	4.7×10^9	54	Insoluble; none (CDT)(b)
	90	8.8×10^9	100	Insoluble; soft
	100	4.7×10^9	54	Insoluble; soft
Octyl acrylate	10	8.8×10^8	10	Degradation
	50	8.8×10^9	100	Insoluble (0); none (CDT)
	90	6.6×10^9	75	Insoluble (3); soft
	100	4.7×10^9	54	Insoluble; soft
Methyl alpha-chloroacrylate	10	8.8×10^8	10	Degradation
	50	8.8×10^8	10	Degradation
	90	8.8×10^8	10	Degradation
	100	8.8×10^8	10	Degradation
Vinyl acetate	10	8.8×10^8	10	Degradation
	50	8.8×10^8	10	Degradation
	90	6.8×10^9	100	Insoluble; none (CDT)
	100	6.6×10^9	75	Insoluble; none (CDT)
Allyl acetate	10	8.8×10^8	10	Degradation
	50	8.8×10^8	10	Degradation
Styrene	10	8.8×10^8	10	Degradation
	50	8.8×10^8	10	None
	90	8.8×10^8	10	None
	100	8.8×10^8	10	None
2,5-Dichlorostyrene	10	8.8×10^8	10	Degradation
	50	8.8×10^8	10	Degradation
	90	8.8×10^8	10	Degradation
	100	8.8×10^8	10	Degradation
Acrylonitrile	10	4.7×10^9	54	Degradation
	20	4.7×10^9	54	Degradation
	10	6.8×10^9	100	Insoluble; none (CDT)
	50	6.6×10^9	75	Insoluble; none (CDT)
1,3-Butadiene	90	4.7×10^9	54	Insoluble; none (CDT)
	10	8.8×10^9	100	Insoluble (0); improvement (FDT)(c)
	20	8.8×10^9	100	Insoluble (0); improvement (FDT)
	30	8.8×10^9	100	Insoluble (0); improvement (FDT)

(a) "(0)" after "Insoluble" indicates material was also insoluble prior to irradiation.

(b) (CDT) stands for Compression Deformation Test, ASTM D 621.

(c) (FDT) stands for Flexural Deformation Test or Heat Distortion Test, ASTM D 648.

TABLE A-53. EFFECTS OF IRRADIATION ON COPOLYMERS OF STYRENE (110)

Comonomer	Per Cent Comonomer	Maximum Radiation Dose		Effects
		Ergs G ⁻¹ (C)	Megaroentgens	
Methyl methacrylate	10	8.8 x 10 ⁸	10	None
	50	8.8 x 10 ⁸	10	None
	90	8.8 x 10 ⁸	10	Degradation
	100	8.8 x 10 ⁸	10	Degradation
Ethyl methacrylate	10	8.8 x 10 ⁸	10	None
	50	8.8 x 10 ⁸	10	None
	90	8.8 x 10 ⁸	10	Degradation
	100	8.8 x 10 ⁸	10	Degradation
Octyl methacrylate	10	8.8 x 10 ⁸	10	None
	50	8.8 x 10 ⁸	10	None
	90	8.8 x 10 ⁸	10	None
	100	8.8 x 10 ⁸	10	None
Methyl acrylate	10	4.7 x 10 ⁹	54	None
	50	8.8 x 10 ⁸	100	Insoluble; none (CDT)(a)
	90	8.8 x 10 ⁸	75	Insoluble (0)(b); none (CDT)
	100	6.6 x 10 ⁹	75	Insoluble; soft
Octyl acrylate	10	8.8 x 10 ⁸	100	Insoluble; none (CDT)
	50	8.8 x 10 ⁸	100	Insoluble; none (CDT)
	90	8.8 x 10 ⁹	100	Insoluble; soft
	100	4.7 x 10 ⁹	54	Insoluble; soft
Vinyl acetate	10	4.7 x 10 ⁹	54	None
	50	8.8 x 10 ⁹	100	Soft
	90	6.6 x 10 ⁹	75	Insoluble; none (CDT)
	100	8.8 x 10 ⁸	10	None
Allyl acetate	10	8.8 x 10 ⁸	100	None
	50	8.8 x 10 ⁸	100	Insoluble; slight improvement (CDT)
	90	8.8 x 10 ⁹	100	Insoluble; improvement (CDT)
	100	4.7 x 10 ⁹	54	Insoluble (0); soft
2,5-Dichlorostyrene	10	8.8 x 10 ⁸	100	Insoluble; none (CDT)
	50	8.8 x 10 ⁸	100	Insoluble; none (CDT)
	90	8.8 x 10 ⁹	100	Insoluble; none (CDT)
	100	4.7 x 10 ⁹	54	Insoluble; none (CDT)

(a) (CDT) stands for Compression Deformation Test.

(b) "(0)" after "Insoluble" indicates material was also insoluble prior to irradiation.

TABLE A-59. RADIATION-INDUCED DISCOLORATIONS IN TRANSPARENT PLASTIC MATERIALS (11)

Absorbed Radiation Dose, ergs g ⁻¹	Descriptive Color Changes for Material Indicated				
	Methyl Methacrylates	Methyl Alpha- Chloroacrylate	MIL-P-8257	Selectron 400 (Fully Cured)	Sierracin 880 (Fully Cured)
Control	Colorless	Colorless	Light-blue tint	Yellow tint	Colorless
1×10^8	Colorless	Light yellow	Light-blue tint		
5×10^8		Yellow			
1×10^9	Colorless	Amber tint	Light-blue tint	Yellow tint	Colorless
3×10^9		Amber tint			
3×10^9		Amber			
5×10^9	Yellow tint		Light-blue tint	Yellow tint	Yellow tint
1×10^8	Light yellow	Brown	Light blue-green	Light yellow	Light yellow
2×10^8	Yellow				
3×10^8		Dark brown			
5×10^8	Yellow		Light blue-green	Yellow	Yellow
1×10^9			Light yellow	Amber tint	Yellow
5×10^9	Dark yellow		Yellow	Amber	Deep yellow
1×10^{10}			Yellow	Deep amber	Amber

TABLE A-5C. RADIATION DOSES FOR THRESHOLD AND 25 PER CENT DAMAGE FOR TRANSPARENT PLASTIC MATERIALS (III)

Properties	Extent of Damage	Radiation Dose, ergs g ⁻¹ , for Indicated Material			
		MIL-P-5423	MIL-P-8184	MIL-P-3257	Sierracin 880
Optical					
Discoloration	Threshold	5×10^7	5×10^7	1×10^8	1×10^8
	25% damage			Not applicable	5×10^7
Luminous	Threshold	5×10^7	3×10^7	5×10^7	5×10^7
Transmittance	25% damage	1×10^7	2×10^8	1×10^9	4×10^8
Haze	Threshold	$> 2 \times 10^8$	$> 5 \times 10^8$	5×10^7	$> 1 \times 10^{10}$
	25% damage			Greater than 1×10^{10}	$> 1 \times 10^{10}$
Index of Refraction	Threshold			Greater than 5×10^9	
	25% damage			Greater than 5×10^9	
Mechanical					
Tensile	Threshold	--	3×10^8	1×10^8	2×10^8
Strength	25% damage	--	2×10^9	$> 1 \times 10^{10}$	3×10^8
Flexural	Threshold	1×10^8	1×10^9	2×10^8	5×10^8
Strength	25% damage	2×10^9	2×10^9	$> 1 \times 10^{10}$	3×10^8
Flexural	Threshold	$> 1 \times 10^{10}$	$> 1 \times 10^{10}$	--	1×10^7
Modulus of Elasticity	25% damage	$> 1 \times 10^{10}$	$> 1 \times 10^{10}$	--	1×10^{10}
Impact	Threshold	1×10^9	5×10^8	1×10^8	1×10^7
Strength	25% damage	2×10^7	2×10^9	1×10^{10}	1×10^8
Thermal	Threshold	--	1×10^9	1×10^9	1×10^8
Heat-Distortion Temperature	25% damage	--	5×10^8	$> 1 \times 10^{10}$	5×10^8
Permanence	Threshold				
Linear	Threshold			Greater than 5×10^9	
Dimension	25% damage			Greater than 5×10^9	
Weight	Threshold			Greater than 5×10^9	
	25% damage			Greater than 5×10^9	
Barcol	Threshold	$> 1 \times 10^8$	$> 1 \times 10^8$	$> 3 \times 10^8$	$> 1 \times 10^{10}$
Hardness	25% damage	$> 1 \times 10^8$	$> 1 \times 10^8$	$> 3 \times 10^8$	$> 1 \times 10^{10}$
Stress-Solvent	Threshold	1×10^8	5×10^7	5×10^8	--
Grazing	25% damage	5×10^8	$> 5 \times 10^8$	1×10^8	--
General					
Specific Gravity	Threshold			Greater than 5×10^8	
	25% damage			Greater than 5×10^8	

TABLE A-61. EFFECTS OF IRRADIATION ON THE MECHANICAL AND PHYSICAL PROPERTIES OF NATURAL RUBBERS WITH SHORE A DUROMETER HARDNESS OF 70 TO 80 AND 40(115)

Integrated Fast-Neutron Flux	$6 \times 10^{14} \text{ n cm}^{-2}$
Integrated Thermal-Neutron Flux	$6 \times 10^{13} \text{ nvt}$
Integrated Gamma Flux	$5 \times 10^{16} \text{ } \gamma \text{ cm}^{-2}$
Total Dose	$2.4 \times 10^9 \text{ ergs g}^{-1} \text{ (C)}$
Environment	
During Irradiation	Air
Postirradiation	Air

Type of Test	Number of Samples		Mean of Samples		$(X_I - X_C) \pm P(a)$	Interpretation
	Control	Irradiated	Control (X_C)	Irradiated (X_I)		
<u>Shore A Durometer Hardness, 70 to 80</u>						
Tensile						
Strength, psi	5	5	3045	2427	-618 \pm 253	Decrease
Elongation, per cent	5	5	322	235	-87 \pm 31	Decrease
Low-Temperature			- 65 F (P) ^(b)	-65 F (P)	--	
Flexibility	2	2	-70 F (F) ^(c)	-70 F (F)	--	No change
Compression						
Set, per cent	2	4	73.0	71.0	-2.0 \pm 3.0	No change
Tear						
Strength, lb in. ⁻¹	5	5	205	128	-77 \pm 32	Decrease
Specific Gravity	1	1	1.18	1.19	--	No change
Hardness, Instantaneous/10 sec	1	1	83/79	80/77	--	No change
<u>Shore A Durometer Hardness, 40</u>						
Tensile						
Strength, psi	5	5	1601	2063	462 \pm 526	No change
Elongation, per cent	5	5	685	670	5 \pm 54	No change
Low-Temperature			-65 F (P) ^(b)	-65 F (P)	--	
Flexibility	2	2	-70 F (F) ^(c)	-70 F (F)	--	No change
Compression						
Set, per cent	2	4	68.0	82.0	-6.0 \pm 3.6	Decrease
Tear						
Strength, lb in. ⁻¹	5	5	151	171	20 \pm 23	No change

TABLE A-61. (Continued)

Type of Test	Number of Samples		Mean of Samples		$(X_I - X_C) \pm p^{(a)}$	Interpretation
	Control	Irradiated	Control (X_C)	Irradiated (X_I)		
Specific Gravity	1	1	1.01	1.01	--	No change
Hardness, Instantaneous/30 sec	1	1	37/32	37/32	--	No change

(a) P = Precision at 95 per cent confidence interval.

(b) (P) = Passed.

(c) (F) = Failed.

TABLE A-62. NATURAL RUBBER FORMULATIONS USED FOR CRYSTALLINITY STUDIES OF STRETCHED IRRADIATED SPECIMENS (117, 118)

	Mare Island Rubber Laboratory Specimen	Massillon Rubber Company Specimen
Material, parts by weight		
Deproteinized pale crepe	100	--
Latex rubber	--	100
Sulfur	2	1
Zinc oxide	3	--
Zinc dibutyldithiocarbamate	0.25	--
2-mercaptobenzothiazole	0.4	--
4-mercaptobenzothiazole and potassium pentamethylenedithiocarbamate mixture	--	0.5
Triethanolamine, heptylated diphenylamine, and heptaldehyde-aniline (a reaction product) mixture	--	2
Wax	--	0.5
Cure, min/F	20/280	Steam cured in a vulcani- zer; time not specified

TABLE A-61. EFFECTS OF IRRADIATION ON THE MECHANICAL PROPERTIES OF GUMA-IRRADIATED ESTANE POLYURETHANE ELASTOMERS (112)

	Estane VC			Estane VC (WR)			Cast Estane		
	Irradiated, crgs g^{-1} (101)			Irradiated, crgs g^{-1} (101)			Irradiated, crgs g^{-1} (101)		
	Original	1.7 x 10 ¹¹	6.4 x 10 ¹¹	Original	1.7 x 10 ¹¹	6.4 x 10 ¹¹	Original	1.7 x 10 ¹¹	6.4 x 10 ¹¹
Tensile Strength, psi	6300	2930	8700	(c)	5100	4000	6500	(c)	8200
300 Per Cent Modulus, psi	1400	--	--	(c)	3700	--	--	(c)	600
Elongation at Break, per cent	625	25	25	(c)	390	75	25	(c)	850
Compression Set, per cent	34	23	26	(c)	63	59	43	(c)	68
Graves Angle Tear Resistance, lb f (inch ^{1/2})	53	15	32	-1	65	16	22	-2	30
Yarnley Resilience, per cent	78	(e)	(e)	(e)	(e)	(e)	(e)	(e)	(e)
Shore D Hardness	40	50	52	67	52	67	75	74	25
Pico Abrasion Index	271	35	25	33	345	42	24	1.3	103
Brittle Point, C	Below -74	-4.5	-25	-15	-63	-12	-25	-25	-40
Melt Flow Temperature, C	124	165	205	222	147	155	167	206	--
Immersion Test, per cent volume	Disolved (THF)	(f)	(f)	(f)	35 (acetone)	53 (acetone)	(f)	(f)	90 (in THF)
Swollen Flex Life, cycles	45,000 (no break)	43	(f)	(f)	65,000 (no break)	144	(c)	(c)	515,500 (no break)

(a)

Composition of Irradiated Estane Polyurethane

	Estane VC		Estane VC (WR)		Cast Estane	
	Diphenylmethane-p,p'-disocyanate (1.00 moles)	Hydroxy poly (tetramethylene adipate), molecular weight ~1000 (1.00 mole)	Methyl methacrylate (2.40 moles)	Hydroxy poly (tetramethylene adipate) (1.10 mole)	Para-phenylene diisocyanate (1.70 moles)	Hydroxy poly (tetramethylene adipate), molecular weight ~2000 (1.00 mole)
Diisocyanate						
Polyester						
Glycol						

(b) Doses originally reported in references: 2 x 10¹¹, 6 x 10¹¹, 10 x 10¹¹.

(c) Too brittle to test.

(d) Crumbled.

(e) Too hard to test.

(f) Swollen sample, too weak to test.

TABLE A-64. RECIPES FOR ADDUCT RUBBERS TESTED
FOR RADIATION STABILITY(127)

	<u>R24 X 916</u>	<u>R24 X 931</u>	<u>R24 X 944</u>
Material, parts by weight			
86% saturated methyl mercaptan adduct of polybutadiene	100.00	--	--
92% saturated methyl mercaptan adduct of polybutadiene	--	100.0	--
65% saturated methyl mercaptan adduct of 67/33 butadiene- acrylonitrile	--	--	100.0
HAF Black	50.0	50.0	50.0
Hydrated Alum	2.0	2.0	2.0
DiCap 40 C	5.0	7.0	4.5
Pine tar	0.5	--	--
Cure, min/°F	60/300	60/330	60/325

TABLE A-65. EFFECT OF GAMMA RADIATION ON THE MECHANICAL PROPERTIES
OF ADDUCT RUBBERS (127)

Material	Exposure Dose		Initial Properties and Per Cent Change						Remarks
	Ergs G ⁻¹ x 10 ⁻⁹	(C) Roentgen x 10 ⁻⁶	Hardness		Elongation		Tensile		
			Shore A	Δ%	Per Cent	Δ%	PS	Δ%	
R24 X 916 (86 per cent saturated methyl mercaptan adduct of polybutadiene)	0	0	70	--	365	--	1990	--	
	C.44	5		6.0		-6.8		11.3	Black
	1.9	22		2.6		-21.9		36.0	
	4.3	55		7.9		-47.9		41.5	
	8.7	100		16.5		-60.3		36.2	
	26	300		17.1		-86.3		12.0	
	44	500		21.1		-89.0		-10.1	
	87	1000		25.0		-95.9		-14.3	
R24 X 931 (92 per cent saturated methyl mercaptan adduct of polybutadiene)	0	0	71	--		--		--	
	C.44	5		0.0		-7.1		5.1	Black
	1.9	22		2.8		-21.4		11.5	
	4.3	55		7.0		-38.8		17.8	
	8.7	100		9.9		-56.1		10.8	
	26	300		16.9		-78.6		-7.7	
	44	500		22.5		-85.7		-27.3	
	87	1000		29.6		-93.9		-60.7	
R24 X 944 (95 per cent saturated methyl mercaptan adduct of polybutadiene)	0	0	78	--		--		--	
	C.44	5		0.0		-11.4		10.4	Black
	1.9	22		3.8		-44.3		19.1	
	4.3	55		7.7		-70.5		-0.1	
	8.7	100		11.5		-79.5		-15.2	
	26	300		17.9		-90.9		-24.6	
	44	1000		21.9		-93.2		-24.6	
	87	1000		25.6		-98.9		-26.1	

TABLE A-66. EFFECTS OF IR RADIATION ON THE MECHANICAL PROPERTIES OF SBR RUBBERS WITH DUREMETER HARDNESSES OF 70 TO 80 AND 10(115)

	Integrated Fast-Neutron Flux		$6 \times 10^{14} \text{ n cm}^{-2}$	
	Integrated Thermal-Neutron Flux		$6 \times 10^{13} \text{ nv}_0 \text{ t}$	
	Integrated Gamma Flux		$5 \times 10^{16} \text{ y cm}^{-2}$	
	Total Dose		$2.4 \pm 10^9 \text{ ergs g}^{-1} \text{ (C)}$	
	Environment			
	During Irradiation		Air	
	Postirradiation		Fuel	

Type of Test	Number of Samples		Mean of Samples		$(X_I - X_C) \pm P^{(a)}$	Interpretation
	Control	Irradiated	Control (X_C)	Irradiated (X_I)		
<u>Shore A Durometer Hardness, 70 to 80</u>						
Tensile Strength, psi	6	6	1771	1840	69 ± 64	Increase
Elongation, per cent	6	6	480	412	-68 ± 14	Decrease
Low-Temperature Flexibility	2	2	-30 F (F) ^(b)	-30 F (F)	--	No change
Compression Set, per cent	2	4	72.5	63.2	-9.3 ± 5.7	Decrease
Tear strength, lb in. ⁻¹	6	6	201	169	-32 ± 7.6	Decrease
Specific Gravity	1	1	1.34	1.35	-	No change
Hardness, instantaneous/30 sec	1	1	94/66	77/67	--	No change
<u>Shore A Durometer Hardness, 40</u>						
Tensile Strength, psi	6	6	2091	1627	-464 ± 206	Decrease
Elongation, per cent	6	6	810	500	-310 ± 65	Decrease
Low-Temperature Flexibility	2	2	-50 F (P) ^(c) -55 F (F)	-50 F (P)	--	No change
Compression Set, per cent	2	4	61.0	48.0	-13.0 ± 2.0	Decrease
Tear Strength, lb in. ⁻¹	6	6	177	179	-7 ± 25	No change

TABLE A-66. (Continued)

Type of Test	Number of Samples		Mean of Samples		$(X_I - \bar{X}_C) \pm p^{(a)}$	Interpretation
	Control	Irradiated	Control (\bar{X}_C)	Irradiated (\bar{X}_I)		
Specific Gravity	1	1	1.09	1.09	--	No change
Hardness						
Instantaneous/30 sec	1	1	49/43	51/43	--	No change

(a) P = Precision at 95 per cent confidence interval.

(b) (F) = Failed.

(c) (P) = Passed.

TABLE A-87. RECIPES FOR NITRILE RUBBERS USED FOR TESTS DETERMINING THE EFFECT OF ACRYLONITRILE CONTENT ON RADIATION STABILITY (127)

	Hanford Sample Designations					
	HW-B17	HW-B18	HW-B20	HW-B21	HW-B22	HW-B23
Material, parts by weight						
Hycar 1000 X 88 (50 per cent acrylonitrile)	100					100
Hycar 1002 (33 per cent acrylonitrile)		100				
Hycar 1042 (33 per cent acrylonitrile)					100	
Hycar 1014 (20 per cent acrylonitrile)			100	100		
Zinc oxide	5	5	5	5	5	5
%MTD	3.5	3.5	3.5	3.0	3.0	3.0
Stearic acid	1.0	1.0	1.0	--	--	--
Santocure	--	--	--	3.0	3.0	3.0
Sulfur	--	--	-	0.3	0.3	0.3
GPF Black	--	--	-	60.0	60.0	60.0
Age Rite Resin D	--	--	--	3.0	3.0	3.0

Notes: Elastomers containing carbon black were cured for 12 minutes at 300 F; those without filler were cured 30 minutes at 310 F.

TABLE A-68. EFFECT OF GAMMA RADIATION ON THE MECHANICAL PROPERTIES OF NITRILE RUBBERS CONTAINING VARIOUS AMOUNTS OF ACRYLONITRILE (12)

Harford Sample Designation	Material	Exposure Dose		Initial Properties and Per Cent Change				Remarks
		Ergs G ⁻¹ (10 ³)	Emulsion x 10 ⁻³	Hardness Shore A	Per Cent Elongation	Tensile Strength PSI	Tensile Strength %	
HW-B17	Hycar 1030 X 88, 50 per cent acrylonitrile, 20 carbon black	0	0	51	585	535	-5.6	Gray-tan
		0.44	3	1.9	-21.4		7.7	Slightly olive
		1.5	22	15.7	-52.1		61.9	Light olive drab
		4.6	55	34.4	-72.6		139.8	Olive drab
		8.7	100	54.9	-88.3		972.0	Brown; broke when bent 180°
HW-B18	Hycar 1032, 33 per cent acrylonitrile, no carbon black	0	0	49	365	300	22.5	Gray-tan
		0.44	5	4.1	1.4		22.6	Slightly olive
		1.5	22	18.4	-45.2		30.9	Light olive drab
		4.6	55	36.7	-80.8		90.1	Olive drab
		8.7	100	51.0	-94.6		644.0	Brown; broke when bent 180°
HW-B20	Hycar 1014, 40 per cent acrylonitrile, no carbon black	0	0	45	290	310	-4.8	Brown-tan
		0.44	5	6.7	-27.6		2.3	Slightly darker
		1.5	22	13.3	-27.6		11.0	"
		4.6	55	23.9	-53.7		13.9	"
		8.7	100	51.1	-79.3		511.0	Brown; broke when bent 180°
HW-B21	Hycar 1014, 20 per cent acrylonitrile, 60 phr carbon black	0	0	76	310	2040	9.5	Black
		0.44	5	-1.3	-5.9		6.5	
		1.5	22	1.3	-12.3		9.0	
		4.6	55	12.5	-43.2		7.4	Stress cracks first appeared
		8.7	100	35.8	-62.2		(a)	Broke when bent 180°
HW-B22	Hycar 1042, 33 per cent acrylonitrile, 60 phr carbon black	0	0	79	305	2940	-1.7	Black
		0.44	5	1.0	-8.2		2.1	
		1.5	22	1.3	-4.9		11.9	
		4.6	55	7.9	-37.7		13.9	
		8.7	100	15.3	-67.2		(a)	Broke when bent 180°
HW-B23	Hycar 1090 X 48, 50 per cent acrylonitrile, 60 phr carbon black	0	0	85	305	2390	2.4	Black
		0.44	5	2.1	-14.0		4.1	
		1.5	22	3.5	-24.3		20.3	
		4.6	55	11.5	-60.5		(a)	
		8.7	100	15.5	-80.3		(a)	Broke when bent 180°
		26	300	17.7	-100.0		(a)	

(a) Exceeded capacity of tensile tester; tensile strength greater than 4000 psi. Another tester was used for the other materials.

TABLE A-69. RECIPES FOR NITRILE RUBBERS USED FOR TESTS
DETERMINING THE EFFECT OF CARBON BLACK
ON RADIATION RESISTANCE⁽¹²⁷⁾

	Hanford Sample Designation				
	B-1	B-2	B-3	B-4	B-5
Material, parts by weight					
Hycar 1002	100.0	100.0	100.0	100.0	100.0
Zinc oxide	5.0	5.0	5.0	5.0	5.0
TMTD	3.5	3.5	3.5	3.5	3.5
Stearic acid	1.0	1.0	1.0	1.0	1.0
PEF Black	5.0	15.0	40.0	60.0	80.0

Note: All compounds cured 30 minutes at 310 F.

TABLE A-70 EFFECT OF CARBON BLACK ON THE RADIATION STABILITY OF NITRILE RUBBER (127)

Hanford Sample Designation	Material	Exposure Dose		Initial Properties and Per Cent Change						Remarks
		Erp G ⁻¹ (G) ± 10 ⁻³	Röntgen x 10 ⁻³	Hardness		Elongation		Tensile Strength		
				Shore A	Δ %	Per Cent	Δ %	PSI	Δ %	
B-1	Hycar 1502 (5 per cent carbon black)	0	0	50		520		660	Black	
		0.44	5		2.6		-5.8		11.4	
		1.9	22		12.0		-34.6		2.0	
		4.8	55		26.6		-65.4		-7.3	
		8.7	100		42.6		-80.8		7.1	
B-2	Hycar 1502 (15 per cent carbon black)	25	300		92.0		-92.3		374.0 (a)	
		0	0	56		575		1630	Black	
		0.44	5		1.8		-14.9		-3.1	
		1.9	22		12.5		-50.9		-25.3	
		4.8	55		25.0		-76.3		-33.5	
B-3	Hycar 1502 (40 per cent carbon black)	8.7	100		37.5		-84.2		-29.7	
		25	300		75.0		-94.7		121.5 (a)	
		0	0	71		425		3005	Black	
		0.44	5		1.4		-5.7		-1.6	
		1.9	22		5.6		-29.9		-26.1	
B-4	Hycar 1502 (60 per cent carbon black)	4.8	55		15.5		-69.0		-31.9	
		8.7	100		25.4		-79.3		-36.0	
		25	300		38.0		-93.1		48.1 (a)	
		0	0	76		295		3135	Black	
		0.44	5		1.2		-8.5		0.4	
B-5	Hycar (30 per cent carbon black)	1.9	22		7.9		-37.3		14.2	
		4.8	55		15.1		-66.1		5.0	
		8.7	100		13.7		-83.1		-2.1	
		25	300		30.3		-96.3		51.4 (a)	
		0	0	82		195		3130	Black	
		0.44	5		1.2		-7.7		-0.2	
		1.9	22		6.1		-35.3		16.1	
		4.8	55		8.8		-64.1		2.0	
		8.7	100		14.5		-74.4		7.4 (a)	
		25	300		22.1		-100.0		109.8 (a)	

(a) Exceeded capacity of tensile tester; tensile strength greater than 4000 psi. Another tester was used for the entire series.

(a) Exceeded capacity of tensile tester; tensile strength greater than 400 psi. Another tester was used for the other materials.

TABLE A-72. EFFECT OF RADIATION ON TENSILE STRENGTH AND ELONGATION OF NITRILE RUBBERS (17)

Material Code	Filter, pli	Conditions	Calculated Dose			Average Tensile Strength, psi	Average Elongation, per cent	Remarks(a)
			Gamma, $\text{crg g}^{-1}(\text{C})$	Neutron, n cm^{-2}	($E > 0.33 \text{ Mev}$)			
<u>High-Air/low-nitile-Crosslink-Fluoropolymer</u>								
1001-1	None	Air	Control	Control	Control	432 ± 85 (b)	730	--
		Open air	2.5×10^3	3.5×10^{15}		435 ± 87	260	No significant difference
		Open air	1.1×10^{10}	5×10^{15}		523 ± 99	65	Increase over Controls
		Open air	1.1×10^{10}	8×10^{15}		577 ± 112	82	Increase over Controls
		Sealed in air	3×10^3	4×10^{15}		358 ± 81	130	No significant difference
		Sealed in air	7×10^3	3×10^{15}		445 ± 56	125	No significant difference
		Immersed in JP-4 fuel	Control	Control		211 ± 8	556	--
		Immersed in JP-4 fuel	1.5×10^{10}	9×10^{16}		214 ± 55	56	No significant difference
1001-2	20 SFF Black	Air	Control	Control		2525 ± 595	760	--
		Open air	1.1×10^{10}	5×10^{15}		2253 ± 214	30	No significant difference
1001-3	20 FES Black	Air	Control	Control		2793 ± 222	806	--
		Open air	3.5×10^3	3.5×10^{15}		2925 ± 330	130	No significant difference
		Open air	1.1×10^{10}	5×10^{15}		3154 ± 670	56	No significant difference
		Open air	1.1×10^{10}	8×10^{15}		3145 ± 420	75	No significant difference
		Immersed in JP-4 fuel	Control	Control		2333 ± 568	700	--
		Immersed in JP-4 fuel	1.5×10^{10}	5×10^{16}		924 ± 312	55	Decreased below Controls
1001-4	30 FEF Black	Air	Control	Control		2843 ± 332	760	--
		Open air	3.5×10^3	3.5×10^{15}		2543 ± 306	144	No significant difference
		Open air	1.1×10^{10}	5×10^{15}		3344 ± 262	55	Increase over Controls
		Open air	1.1×10^{10}	8×10^{15}		3611 ± 472	75	Increase over Controls
1001-5	40 FEF Black	Air	Control	Control		2522 ± 426	670	--
		Open air	3.5×10^3	3.5×10^{15}		2567 ± 480	125	No significant difference
		Open air	1.1×10^{10}	5×10^{15}		3210 ± 455	62	Increase over Controls
		Open air	1.1×10^{10}	8×10^{15}		2533 ± 410	60	Increase over Controls
		Sealed in air	3×10^3	6×10^{15}		2963 ± 406	140	Increase over Controls
		Sealed in air	1.1×10^{10}	8×10^{15}		3192 ± 440	56	Increase over Controls
		Sealed in nitrogen	8×10^3	4×10^{15}		2713 ± 550	100	No significant difference
		Sealed in nitrogen	9×10^3	9×10^{16}		3173 ± 356	50	Increase over Controls

TABLE A-7E. (Continued)

Material Code	Filler, phr	Conditions	Calculated Dose		Average Tensile Strength, psi	Average Elongation, per cent	Remarks(a)
			Gammat, erg g ⁻¹ (C)	Neutron, n cm ⁻² (E > .53 Mev)			
Medium-High-Acrylonitrile-Copoly Elastomers, Low-Temperature Polymerized							
1052-1	None	Air	Control	Control	388 ± 64	549	--
		Open air	3.5 x 10 ¹⁵	3.5 x 10 ¹⁵	395 ± 58	120	No significant difference
		Open air	1.1 x 10 ¹⁶	5 x 10 ¹⁵	473 ± 91	99	Increase over Control
		Open air	1.1 x 10 ¹⁶	5 x 10 ¹⁵	554 ± 127	53	Increase over Control
		Immersed in JP-4 fuel	Control	Control	258 ± 6	425	--
		Immersed in JP-4 fuel	1.5 x 10 ¹⁶	3 x 10 ¹⁵	238 ± 88	60	No significant difference
1052-2	20 FEF Black	Air	Control	Control	1324 ± 347	817	--
		Open air	3.5 x 10 ¹⁵	3.5 x 10 ¹⁵	1245 ± 145	105	Decrease below Controls
		Open air	1.1 x 10 ¹⁶	5 x 10 ¹⁵	1155 ± 234	65	Decrease below Controls
		Open air	1.1 x 10 ¹⁶	5 x 10 ¹⁵	1242 ± 143	55	Decrease below Controls
		Immersed in JP-4 fuel	Control	Control	1358 ± 38	630	--
		Immersed in JP-4 fuel	1.5 x 10 ¹⁶	3 x 10 ¹⁵	251 ± 80	30	Decrease below Controls
1052-3	40 FEF Black	Air	Control	Control	2387 ± 175	750	--
		Open air	1.1 x 10 ¹⁶	5 x 10 ¹⁵	2175 ± 218	90	No significant difference
		Sealed in air	3.5 x 10 ¹⁵	4 x 10 ¹⁵	2161 ± 230	100	No significant difference
		Air	Control	Control	2761 ± 105	583	--
		Open air	3.5 x 10 ¹⁵	3.5 x 10 ¹⁵	2550 ± 375	142	No significant difference
		Open air	1.1 x 10 ¹⁶	5 x 10 ¹⁵	2332 ± 170	135	Decrease below Controls
1052-4	60 SBF Black	Open air	Control	Control	2336 ± 336	89	Decrease below Controls
		Open air	1.1 x 10 ¹⁶	3 x 10 ¹⁵			
		Open air					
		Open air					
		Open air					
		Open air					
Commercial Elastomers							
Polymer 105-15	Unknown	Air	Control	Control	2532 ± 303	104	--
		Open air	1.1 x 10 ¹⁶	5 x 10 ¹⁵	3795 ± 485	43	
		Open air SS18 oil	1.1 x 10 ¹⁶	5 x 10 ¹⁵	2854 ± 494	31	No significant difference
		Air	Control	Control	3750 ± 356	0	--
		Open air SS18 oil	1.1 x 10 ¹⁶	5 x 10 ¹⁵	1755 ± 456	0	Decrease below Controls
		Open air SS18 oil	1.1 x 10 ¹⁶	5 x 10 ¹⁵			

(a) Remarks pertain only to "Average Tensile Strength" column.

(b) Precision at 95 per cent confidence interval.

TABLE A-73. EFFECTS OF IRRADIATION ON THE MECHANICAL AND PHYSICAL PROPERTIES OF
BUNA-N RUBBERS WITH SHORE A DUROMETER HARDNESSES OF 70 TO 80 AND 40 (115)

Integrated Fast-Neutron Flux	$6 \times 10^{14} \text{ n cm}^{-2}$
Integrated Thermal-Neutron Flux	$6 \times 10^{13} \text{ n cm}^{-2}$
Integrated Gamma Flux	$5 \times 10^{16} \text{ } \gamma \text{ cm}^{-2}$
Total Dose	$2.4 \times 10^9 \text{ ergs}^{-1} \text{ (C)}$
Environment	
During Irradiation	Air
Postirradiation	Fuel

Type of Test	Number of Samples		Mean of Samples		$(X_I - X_C) \pm p(a)$	Interpretation
	Control	Irradiated	Control (X_C)	Irradiated (X_I)		
<u>Shore A Durometer Hardness, 70 to 80</u>						
Tensile						
Strength, psi	5	5	2340	2732	393 ± 137	Increase
Elongation, per cent	5	5	330	275	-55 ± 27	Decrease
Low-Temperature Flexibility	4	4	-30 F (F) ^(b)	-30 F (F)	--	No change
Compression						
Set, per cent	2	4	56.0	50.0	-6 ± 3.2	Decrease
Tear Strength, lb in. ⁻¹	5	5	200	182	-18 ± 10	No change
Specific Gravity	1	1	1.20	1.20	--	No change
Hardness, instantaneous/30 sec	1	1	80/72	83/74	--	No change
<u>Shore A Durometer Hardness, 40</u>						
Tensile						
Strength, psi	5	5	2393	2423	30 ± 126	No change
Elongation, per cent	5	5	416	436	21 ± 19	Increase
Low-Temperature Flexibility	4	3	-45 F (P) ^(c) -50 F (F)	-45 F (P) -50 F (F)	-- --	No change
Compression						
Set, per cent	2	4	49.6	49.0	-0.6 ± 0.6	No change
Tear Strength, lb in. ⁻¹	5	5	144	132	-12 ± 19	No change

TABLE A-75. (Continued)

Type of Test	Number of Samples		Mean of Samples		$(X_I - X_C) \pm p^{(a)}$	Interpretation
	Control	Irradiated	Control (X_C)	Irradiated (X_I)		
Specific Gravity	1	1	1.20	1.21	--	No change
Hardness, Instantaneous/30 sec	1	1	50/45	52/47	--	No change

(a) P = Precision at 95 per cent confidence interval.

(b) (F) = Failed.

(c) (P) = Passed.

TABLE A-74. COMPARISON OF MECHANICAL PROPERTIES OF NITRILE RUBBER PACKING COMPOUND(a) AFTER IRRADIATION AT ROOM TEMPERATURE AND AT 158 F, AND AFTER HEAT AGING AT 158 F(11,51)

Time of Irradiation or Heat Aging(b), days	Radiation Dose, ergs g ⁻¹ (C) x 10 ⁻⁹	Irradiated					
		Irradiated at RT		Irradiated at 158 F		Heat Aged at 158 F	
		Tested at RT	Tested at 158 F(c)	Tested at RT	Tested at 158 F	Tested at RT	Tested at 158 F
<u>Tensile Strength, psi</u>							
0	0	2040	530	2040	530	2040	530
1-3/8	0.84	--	--	1970	630(d)	--	--
2-3/4	1.58	--	--	1450	550(d)	--	--
3-1/3	--	--	--	--	--	--	580
3-1/2	2.1	1660	610	--	--	--	--
5-1/2	3.26	--	--	1310	430(d)	--	--
7	4.2	1340	500	--	--	--	--
9-2/3	5.87	--	--	1370	540(d)	--	--
14	8.4	1130	450	--	--	--	630
21	12.6	Broke	450	--	--	--	--
28	--	--	--	--	--	2000	--
56	--	--	--	--	--	1750	630
70	--	--	--	--	--	2050	--
<u>Elongation, per cent</u>							
0	0	500	290	500	290	500	290
1-3/8	0.84	--	--	350	260(d)	--	--
2-3/4	1.58	--	--	300	190(d)	--	--
3-1/3	--	--	--	--	--	--	280
3-1/2	2.1	260	180	--	--	--	--
5-1/2	3.26	--	--	190	140(d)	--	--
7	4.2	140	80	--	--	--	--
9-2/3	5.87	--	--	130	100(d)	--	--
14	8.4	80	50	--	--	--	240
21	12.6	Broke	30	--	--	--	--
28	--	--	--	--	--	340	--
56	--	--	--	--	--	290	190
70	--	--	--	--	--	300	--
<u>Hardness, Shore A</u>							
0	0	48	48	48	48	48	48
1-3/8	0.84	--	--	53	51	--	--
2-3/4	1.58	--	--	56	56	--	--
3-1/3	--	--	--	--	--	--	--
3-1/2	2.1	57	62	--	--	--	--
5-1/2	3.26	--	--	60	60	--	--
7	4.2	68	70	--	--	--	--
9-2/3	5.87	--	--	69	69	--	--
14	8.4	77	76	--	--	--	--
21	12.6	Broke	82	--	--	--	--
28	--	--	--	--	--	53	--
70	--	--	--	--	--	57	--

TABLE A-74. (Continued)

Time of Irradiation or Heat Aging ^(b) , days	Radiation Dose, ergs g ⁻¹ (C) x 10 ⁻⁹	Irradiated					
		Irradiated at RT		Irradiated at 158 F		Heat Aged at 158 F	
		Tested at RT	Tested at 158 F(c)	Tested at RT	Tested at 158 F	Tested at RT	Tested at 158 F
		200 Per Cent Modulus, psi					
0	0	300	310	300	310	300	310
1-3/8	0.84	--	--	630	490(d)	--	--
2-3/4	1.68	--	--	740	Broke	--	--
3-1/4	--	--	--	--	--	--	380
4-1/2	2.51	1030	Broke	--	--	--	--
5-1/2	3.36	--	--	Broke	Broke	--	--
7	4.2	Broke	Broke	--	--	--	--
9-2/3	5.67	--	--	Broke	Broke	--	--
14	8.4	Broke	Broke	--	--	--	470
21	12.6	Broke	Broke	--	--	--	--
28	--	--	--	--	--	550	--
56	--	--	--	--	--	780	--
70	--	--	--	--	--	1030	Broke

(a) Hycar 1001:Hycar 1002, 80:20.

(b) Test values for the heat-aged samples are placed in their approximate relationship to the samples irradiated at 158 F based on the time of exposure to the elevated temperature. The time of irradiation was computed by dividing the exposure dose by the dose rate, $2.52 \times 10^7 \text{ ergs g}^{-1} (\text{C}) \text{ hr}^{-1}$, the radiation flux to which the samples were exposed at the Brookhaven National Laboratory Gamma Facility.(c) The samples irradiated at room temperature and tested at 158 F were irradiated at the Materials Testing Reactor Gamma Facility. The radiation doses were slightly higher than those received by the samples irradiated at the Brookhaven National Laboratory Gamma Facility. Exposure doses at MTR were 0 , 2.2×10^9 , 4.4×10^9 , 8.4×10^9 , and $1.4 \times 10^{10} \text{ ergs g}^{-1} (\text{C})$.

(d) Four dumbbells tested.

TABLE A-75. COMPARISON OF MECHANICAL PROPERTIES OF NITRILE RUBBER SELF-SEALING FUEL-COOL-LINER STOCK(a) AFTER IRRADIATION AT 158 F(11,50) TEMPERATURE AND AT 158 F, AND AFTER HEAT AGING AT 158 F(11,50)

Time of Irradiation Heat Aging(b), days	Radiation Dose ergs/g ¹ (C) x 10 ⁻⁹	Irradiated					
		Irradiated at RT		Irradiated at 158 F		Heat Aged at 158 F	
		Tested at RT	Tested at 158 F(c)	Tested at RT	Tested at 158 F	Tested at RT	Tested at 158 F
Tensile Strength, psi							
0	0	2280	1450	2280	1450	2280	1450
1-3/8	0.84	--	--	2310	1510	--	--
2-3/4	1.68	--	--	2390	1590	--	--
3-1/2	2.1	2480	1600	--	--	--	--
5-1/2	3.36	--	--	2480	1440	--	--
7	4.2	2420	1590	--	--	--	--
9-2/3	5.87	--	--	2750	1260	--	--
14	8.4	2550	1360	--	--	--	--
20	--	--	--	--	--	--	--
21	12.6	Broke	1430	--	--	--	1480
25	--	--	--	--	--	--	--
90	--	--	--	--	--	2160	--
110	--	--	--	--	--	2280	1560
Elongation, percent							
0	0	460	310	460	310	460	310
1-3/8	0.84	--	--	320	250	--	--
2-3/4	1.68	--	--	300	180	--	--
3-1/2	2.1	220	150	--	--	--	--
5-1/2	3.36	--	--	190	140	--	--
7	4.2	170	100(0)	--	--	--	--
9-2/3	5.87	--	--	150	80	--	--
14	8.4	80	30	--	--	--	--
20	--	--	--	--	--	--	--
21	12.6	Broke	40	--	--	--	200
25	--	--	--	--	--	--	--
90	--	--	--	--	--	270	--
110	--	--	--	--	--	210	180
Hardness, Shore A							
0	0	57	--	57	57	57	57
1-3/8	0.84	--	--	60	61	--	--
2-3/4	1.68	--	--	65	65	--	--
3-1/2	2.1	70	71	--	--	--	--
5-1/2	3.36	--	--	70	70	--	--
7	4.2	74	75	--	--	--	--
9-2/3	5.87	--	--	75	75	--	--
14	8.4	82	85	--	--	--	--
20	--	--	--	--	--	--	--
21	12.6	--	87	--	--	--	--
25	--	--	--	--	--	65	--
110	--	--	--	--	--	66	--

TABLE A-75. (Continued)

Time of Irradiation or Heat Aging ^(b) , days	Radiation Dose, ergs g ⁻¹ (C) x 10 ⁻⁹	Irradiated					
		Irradiated at RT		Irradiated at 158 F		Heat Aged at 158 F	
		Tested at RT	Tested at 158 F(c)	Tested at RT	Tested at 158 F	Tested at RT	Tested at 158 F
		70 Per Cent Modulus, psi					
0	0	840	860	840	860	840	860
1-3/8	0.84	--	--	1370	1190	--	--
2-3/4	1.68	--	--	1520	Broke	--	--
3-1/2	2.5	2270	Broke	--	--	--	--
5-1/2	3.36	--	--	Broke	Broke	--	--
7	4.2	Broke	Broke	--	--	--	--
9-7/8	5.87	--	--	Broke	Broke	--	--
14	8.4	Broke	Broke	--	--	--	--
20	--	--	--	--	--	--	1440 ^(e)
21	12.6	Broke	Broke	--	--	--	--
25	--	--	--	--	--	1620	--
110	--	--	--	--	--	2120	--

(a) Hycar 1011.

(b) Test values for the heat-aged samples are placed in their approximate relationship to the samples irradiated at 158 F based on the time of exposure to the elevated temperature. The time of irradiation was computed by dividing the exposure dose by the dose rate, 2.52×10^7 ergs g⁻¹(C) hr⁻¹, the radiation flux to which the samples were exposed at the Brookhaven National Laboratory Gamma Facility.(c) The samples irradiated at room temperature and tested at 158 F were irradiated at the Materials Testing Reactor Gamma Facility. The radiation doses were slightly higher than those received by the samples irradiated at the Brookhaven National Laboratory Gamma Facility. Exposure doses at MTR were 0, 2.3×10^9 , 4.6×10^9 , 9.9×10^9 , and 1.3×10^{10} ergs g⁻¹(C).

(d) Four dumbbells tested.

(e) Three dumbbells tested.

TABLE A-76. COMPARISON OF MECHANICAL PROPERTIES OF NBR-SBR HOSE TUBE STOCK^(a) AFTER IRRADIATION AT ROOM TEMPERATURE AND AT 158 F, AND AFTER HEAT AGING AT 158 F^(11,51)

Time of Irradiation or Heat Aging ^(b) , days	Radiation Dose, mrads g ⁻¹ (C) x 10 ⁻⁹	Irradiated ^(c)					
		Irradiated at RT		Irradiated at 158 F		Heat Aged at 158 F	
		Tested at RT	Tested at 158 F (C)	Tested at RT	Tested at 158 F	Tested at RT	Tested at 158 F
Tensile Strength, psi							
0	0	2240	10	2240	1510	2240	1510
1-3/8	0.84	--	--	2510	1690	--	--
2-3/4	1.68	--	--	2580	1530	--	--
3-1/2	2.1	2460	1640	--	--	--	--
5-1/2	3.36	--	--	2150	1530	--	--
7	4.2	2610	1760	--	--	--	--
9-2/3	5.87	--	--	2320	1780	--	--
14	8.4	2620	1840	--	--	--	--
20	--	--	--	--	--	--	1750
21	12.6	Broke	1720	--	--	--	--
25	--	--	--	--	--	2270	--
90	--	--	--	--	--	--	1840
110	--	--	--	--	--	2620	--
Elongation, per cent							
0	0	200	150	200	150	200	150
1-3/8	0.84	--	--	150	110	--	--
2-3/4	1.68	--	--	140	100	--	--
3-1/2	2.1	150	90	--	--	--	--
5-1/2	3.36	--	--	100	80	--	--
7	4.2	110	70	--	--	--	--
9-2/3	5.87	--	--	90	70	--	--
14	8.4	80	80	--	--	--	--
20	--	--	--	--	--	--	100
21	12.6	Broke	50	--	--	--	--
25	--	--	--	--	--	110	--
90	--	--	--	--	--	--	80
110	--	--	--	--	--	90	--
Hardness, Shore A							
0	0	71	71	71	71	71	71
1-3/8	0.84	--	--	75	75	--	--
2-3/4	1.68	--	--	78	78	--	--
3-1/2	2.1	80	81	--	--	--	--
5-1/2	3.36	--	--	80	--	--	--
7	4.2	84	85	--	--	--	--
9-2/3	5.87	--	--	85	--	--	--
14	8.4	85	88	--	--	--	--
20	--	--	--	--	--	--	--
21	12.6	--	91	--	--	--	--
25	--	--	--	--	--	80	--
110	--	--	--	--	--	83	--

TABLE A-7b. (Continued)

Time of Irradiation or Heat Aging(b), days	Radiation Dose, ergs g ⁻¹ (C) x 10 ⁻⁹	Irradiated					
		Irradiated at RT		Irradiated at 158 F		Heat Aged at 158 F	
		Tested at RT	Tested at 158 F(c)	Tested at RT	Tested at 158 F	Tested at RT	Tested at 158 F
		200 Per Cent Modulus, psi					
0	0	Broke	Broke	Broke	Broke	Broke	Broke
1-3/8	0.84	--	--	Broke	Broke	--	--
2-3/4	1.68	--	--	Broke	Broke	--	--
3-1/2	2.5	Broke	Broke	--	--	--	--
5-1/2	3.36	--	--	Broke	Broke	--	--
7	4.2	Broke	Broke	--	--	--	--
9-2/3	5.87	--	--	Broke	Broke	--	--
14	8.4	Broke	Broke	--	--	--	--
20	--	--	--	--	--	--	Broke
21	12.6	Broke	Broke	--	--	--	--
28	--	--	--	--	--	Broke	--
90	--	--	--	--	--	--	Broke

(a) Hycar 1043:BNR 1001, 85:13,7.

(b) Test values for the heat-aged samples are placed in their approximate relationship to the samples irradiated at 158 F based on the time of exposure to the elevated temperature. The time of irradiation was computed by dividing the exposure dose by the dose rate, $2.52 \times 10^7 \text{ ergs g}^{-1}(\text{C}) \text{ hr}^{-1}$, the radiation flux to which the samples were exposed at the Brookhaven National Laboratory Gamma Facility.(c) The samples irradiated at room temperature and tested at 158 F were irradiated at the Materials Testing Reactor Gamma Facility. The radiation doses were slightly higher than those received by the samples irradiated at the Brookhaven National Laboratory Gamma Facility. Exposure doses at MTR were 0 , 2.2×10^9 , 4.4×10^9 , 8.9×10^9 , and $1.3 \times 10^{10} \text{ ergs g}^{-1}(\text{C})$.

TABLE A-71. COMPARISON OF MECHANICAL PROPERTIES OF NITRILE RUBBER-VINYLBLENDE
BLADDER STOCK(S) AFTER IRRADIATION AT ROOM TEMPERATURE AND AT
158 F., AND AFTER HEAT AGING AT 158 F. (11,51)

Time of Irradiation or Heat Aging ^(b) , Days	Radiation Dose, Mr. g-g-1 (C) x 10 ⁻²	Irradiated					
		Irradiated at RT		Irradiated at 158 F		Heat Aged at 158 F	
		Tested at RT	Tested at 158 F (c)	Tested at RT	Tested at 158 F	Tested at RT	Tested at 158 F
<u>Tensile Strength, psi</u>							
0	0	2270	1490	2270	1490	2270	1490
1-3/8	0.84	--	--	2310	1610	--	--
2-3/4	1.68	--	--	2290	1550	--	--
3-1/2	2.1	2330	1420	--	--	--	--
5-1/2	3.36	--	--	2510	1470	--	--
7	4.2	2350	1750	--	--	--	--
9-2/3	5.87	--	--	2550	1370	--	--
14	8.4	1750	1630	--	--	--	--
20	--	--	--	--	--	--	1420
21	12.6	Broke	1660	--	--	--	--
25	--	--	--	--	--	2310	--
90	--	--	--	--	--	--	1400
110	--	--	--	--	--	2320	--
<u>Elongation, per cent</u>							
0	0	420	380	420	380	420	380
1-3/8	0.84	--	--	300	300	--	--
2-3/4	1.68	--	--	280	200	--	--
3-1/2	2.1	170	170	--	--	--	--
5-1/2	3.36	--	--	150	110	--	--
7	4.2	140	90	--	--	--	--
9-2/3	5.87	--	--	90	60	--	--
14	8.4	40	90	--	--	--	--
20	--	--	--	--	--	--	230
21	12.6	Broke	30	--	--	--	--
25	--	--	--	--	--	310	--
90	--	--	--	--	--	--	210
<u>Hardness, Shore A</u>							
0	0	65	--	65	65	65	65
1-3/8	0.84	--	--	66	66	--	--
2-3/4	1.68	--	--	70	70	--	--
3-1/2	2.1	75	80	--	--	--	--
5-1/2	3.36	--	--	75	76	--	--
7	4.2	80	83	--	--	--	--
9-2/3	5.87	--	--	81	85	--	--
14	8.4	90	91	--	--	--	--
20	--	--	--	--	--	--	--
21	12.6	--	95	--	--	--	--
25	--	--	--	--	--	79	--
110	--	--	--	--	--	70	--

TABLE A-11. (Continued.)

Time of Irradiation or Heat Aging(a), days	Radiation Dose, $\text{e}^{-32} \text{ g}^{-1} (\text{G})$ $\times 10^{-9}$	Irradiated					
		Irradiated at RT		Irradiated at 158 F		Heat Aged at 158 F	
		Tested at RT	Tested at 158 F(c)	Tested at RT	Tested at 158 F	Tested at RT	Tested at 158 F
		200 Per Cent Modulus, psi					
0	0	1170	730	1170	730	1170	739
1-3/8	0.84	--	--	1390	1080	--	--
2-3/4	1.68	--	--	1690	1550	--	--
3-1/2	2.1	Broke	Broke	--	--	--	--
5-1/2	3.36	--	--	Broke	Broke	--	--
7	4.2	Broke	Broke	--	--	--	--
9-2/3	5.87	--	--	Broke	Broke	--	--
14	8.4	Broke	Broke	--	--	--	--
20	--	--	--	--	--	--	1130
24	12.6	Broke	Broke	--	--	--	--
25	--	--	--	--	--	1620	--
90	--	--	--	--	--	--	1430(d)
110	--	--	--	--	--	1910	--

(a) Hycar 1043; VYNY; Hycar 1112, 100; 20; 12.

(b) Test values for the heat-aged samples are placed in their approximate relationship to the samples irradiated at 158 F based on the time of exposure to the elevated temperature. The time of irradiation was computed by dividing the exposure dose by the dose rate, $2.52 \times 10^7 \text{ e}^{-32} \text{ g}^{-1} (\text{G}) \text{ hr}^{-1}$, the radiation flux to which the samples were exposed at the Brookhaven National Laboratory Gamma Facility.(c) The samples irradiated at room temperature and tested at 158 F were irradiated at the Materials Testing Reactor Gamma Facility. The radiation doses were slightly higher than those received by the samples irradiated at the Brookhaven National Laboratory Gamma Facility. Exposure doses at MTR were 0, 2.2×10^9 , 4.4×10^9 , 6.9×10^9 , and $1.3 \times 10^{10} \text{ e}^{-32} \text{ g}^{-1} (\text{G})$.

(d) Four dumbbells tested.

TABLE A-78. ROOM-TEMPERATURE DECOMPOSITION OF POLYMER AND RUBBER ADHESIVE COMPOUNDS IRRADIATED IN AIR AND IN ZINC ARYLPHOSPHATE OIL (GALVANIC HYDRAULIC FLUID)⁽⁵¹⁾

Compound	Antirad	Medium	days	per cent	Compression Set After Exposure at 23×10^3 $\text{erg g}^{-1} (\text{C})$, per cent	Dose Required for 50 Per Cent Set, $\text{erg g}^{-1} (\text{C}) \times 10^{-3}$
Hycar packing compound	None	Air	46	19.6	91.8	0.44
	Akroflex C	Air	47	16.4	87.0	0.61
	Quinhydrone	Air	47	20.8	82.6	0.66
	None	Hydraulic fluid	71	14.6	92.3	0.30
	Akroflex C	Hydraulic fluid	72	14.7	80.7	0.46
	Quinhydrone	Hydraulic fluid	73	14.3	72.7	1.33
Fuel-coil-liner stock	None	Air	47	12.4	88.6	0.78
	Akroflex C	Air	47	9.4	72.6	1.39
	Quinhydrone	Air	44	25.8	80.6	1.87
	None	Hydraulic fluid	71	11.0	80.6	0.86
	Akroflex C	Hydraulic fluid	74	10.3	70.8	1.87
	Quinhydrone	Hydraulic fluid	86	18.7	61.8	1.33
Nitrile rubber- vinylite bladder stock	None	Air	47	22.4	82.3	0.78
	Akroflex C	Air	49	22.3	82.2	1.31
	Quinhydrone	Air	48	31.0	83.9	1.39
	None	Hydraulic fluid	76	27.6	80.8	0.78
	Akroflex C	Hydraulic fluid	80	21.2	81.4	1.29
	Quinhydrone	Hydraulic fluid	77	27.3	80.7	1.22
NBR-SBR tube stock	None	Air	47	12.2	82.6	1.13
	Akroflex C	Air	46	12.6	77.0	1.22
	Quinhydrone	Air	47	10.0	74.0	1.31
	None	Hydraulic fluid	50	11.0	83.3	0.78
	Akroflex C	Hydraulic fluid	70	12.3	70.1	1.07
	Quinhydrone	Hydraulic fluid	71	13.1	73.2	1.46

TABLE A-70. EFFECT OF RADIATION ON COMPRESSION SET OF NITRILE RUBBERS⁽¹⁾

Material Code ^(a)	Condition ^(b)	Calculated Dose		Compression Set, per cent
		Gamma, ergs g ⁻¹ (C)	Neutron, n cm ⁻² (E > 0.39 Mev)	
1052-4 (medium-high acrylonitrile content)	Compressed 650 hours	Control	Control	10.2 (average)
1052-4	Compressed 144 hours before and 500 hours after irradiation	3.3×10^{11}	3.5×10^{16}	78.5 (average)

(a) See Table A-18 for material composition.

(b) Compression set was tested in accordance with ASTM D395-56 with the exception that the specimens were not subjected to temperature variations.

TABLE A-80. EFFECTS OF IRRADIATION ON THE MECHANICAL AND PHYSICAL PROPERTIES OF NEOPRENE RUBBERS WITH SHORE A DUROMETER HARDNESSES OF 70 TO 80 AND 40(115)

Integrated Fast-Neutron Flux	$6 \times 10^{14} \text{ n/cm}^2$
Integrated Thermal-Neutron Flux	$6 \times 10^{13} \text{ n/cm}^2$
Integrated Gamma Flux	$6 \times 10^{16} \text{ r/cm}^2$
Total Dose	$2.4 \times 10^9 \text{ rads g}^{-1} \text{ (C)}$
Environment	
During Irradiation	Air
Postirradiation	Fuel

Type of Test	Number of Samples		Mean of Samples		$(X_1 - X_C) \pm P^{(a)}$	Interpretation
	Control	Irradiated	Control (X_C)	Irradiated (X_1)		
<u>Shore A Durometer Hardness, 70 to 80</u>						
Tensile						
Strength, psi	5	5	2149	2114	-35 ± 135	No change
Elongation, per cent	5	5	252	255	3 ± 17	No change
Low-Temperature Flexibility	5	5	-30 P (P) ^(b)	-30 P (P)		No change
Compression Set, per cent	2	4	19.5	21.0	1.5 ± 1.9	No change
Tear Strength, lb in. ⁻¹	5	5	219	182	-37 ± 11	Decrease
Specific Gravity	1	1	1.40	1.48		No change
Hardness						
Instantaneous/30 sec	1	1	65/61	65/64		No change
<u>Shore A Durometer Hardness, 40</u>						
Tensile						
Strength, psi	4	5	1844	1817	-27 ± 240	No change
Elongation, per cent	5	5	414	410	-4 ± 40	No change
Low-Temperature Flexibility	2	2	-30 P (P) ^(c) -35 P (P)	-30 P (P) -35 P (P)		No change
Compression Set, per cent	2	4	64.0	61.0	-3.0 ± 3.0	No change
Tear Strength, lb in. ⁻¹	5	5	160	165	$+5 \pm 29$	No change
Specific Gravity	1	1	1.32	1.31		No change
Hardness						
Instantaneous/30 sec	1	1	43/36	45/41		No change

(a) P = Precision at 95 per cent confidence interval.

(b) (F) = Failed.

(c) (P) = Passed.

TABLE A-81. COMPARISON OF MECHANICAL PROPERTIES OF NEOPRENE GN WIRE INSULATION AFTER IRRADIATION AT ROOM TEMPERATURE AND AT 158 F, AND AFTER HEAT AGING AT 158 F^{(1), (2)}

Time of Irradiation or Heat Aging ^(a) , days	Radiation Dose, mrads μ^{-1} (C) $\times 10^{-9}$	Irradiated					
		Irradiated at RT		Irradiated at 158 F		Heat Aged at 158 F	
		Tested at RT	Tested at 158 F(b)	Tested at RT	Tested at 158 F	Tested at RT	Tested at 158 F
Tensile Strength, psi							
0	0	1430	860	1430	860	1430	860
1-1/2	0.84	--	--	1280	720	--	--
3	1.68	--	--	1180	620	--	--
3-1/3	--	--	--	--	--	1160	860
3-3/4	2.1	1270	840	--	--	--	--
6	4.36	--	--	1080(c)	600	--	--
7	--	--	--	--	--	1370	880
7-1/2	4.2	1150	890	--	--	--	--
10-1/2	5.87	--	--	1150	740	--	--
14	--	--	--	--	--	1360	810
15	8.4	1490	1230	--	--	--	--
22-1/2	12.6	Broke	1400	--	--	--	--
28	--	--	--	--	--	1360	860
45	--	--	--	--	--	--	840
170	--	--	--	--	--	1470	--
Elongation, per cent							
0	0	650	650	650	650	650	650
1-1/2	0.84	--	--	570	500	--	--
3	1.68	--	--	330	310	--	--
3-1/3	--	--	--	--	--	300	540
3-3/4	2.1	420	410	--	--	--	--
6	4.36	--	--	200	240	--	--
7	--	--	--	--	--	610	600
7-1/2	4.2	180	120	--	--	--	--
10-1/2	5.87	--	--	220	100	--	--
14	--	--	--	--	--	480	410
15	8.4	70	50	--	--	--	--
22-1/2	12.6	Broke	30	--	--	--	--
28	--	--	--	--	--	420	400
45	--	--	--	--	--	--	400
170	--	--	--	--	--	390	--
Hardness, Shore A							
0	0	76	--	76	76	75	--
1-1/2	0.84	--	--	77	79	--	--
3	1.68	--	--	83	81	--	--
3-1/3	--	--	--	--	--	77	--
3-3/4	2.1	83	85	--	--	--	--
6	4.36	--	--	85	85	--	--
7	--	--	--	--	--	78	--
7-1/2	4.2	87	88	--	--	--	--
10-1/2	5.87	--	--	88	90	--	--
14	--	--	--	--	--	79	--
15	8.4	91	94	--	--	--	--
22-1/2	12.6	Broke	95	--	--	--	--
28	--	--	--	--	--	80	--
45	--	--	--	--	--	--	--
170	--	--	--	--	--	84	--

TABLE A-81. (Continued)

Time of Irradiation or Heat Aging ^(a) , days	Radiation Dose, ergs g ⁻¹ (C) × 10 ⁻⁹	200 Per Cent Modulus, psi					
		Irradiated at RT		Irradiated at 158 F		Heat Aged at 158 F	
		Tested at RT	Tested at 158 F ^(b)	Tested at RT	Tested at 158 F	Tested at RT	Tested at 158 F
0	0	870	490	870	490	870	490
1-1/2	0.84	--	--	790	470	--	--
3	1.68	--	--	1640	550(c)	--	--
3-1/3	--	--	--	--	--	990	590
4-3/4	2.1	960	840	--	--	--	--
6	3.36	--	--	960	580	--	--
7	--	--	--	--	--	1040	650
7-1/2	4.2	Broke	Broke	--	--	--	--
10-1/2	5.8"	--	--	1080(c)	Broke	--	--
14	--	--	--	--	--	1050	610
15	8.4	Broke	Broke	--	--	--	--
22-1/2	12.6	Broke	Broke	--	--	--	--
28	--	--	--	--	--	1040	700
45	--	--	--	--	--	--	700
170	--	--	--	--	--	1470	--

(a) Test values for the heat-aged samples are placed in their approximate relationship to the samples irradiated at 158 F based on the time of exposure to the elevated temperature. The time of irradiation was computed by dividing the exposure dose by the dose rate, 2.15×10^7 ergs g⁻¹ (C) hr⁻¹, the radiation flux to which the samples were exposed at the Brookhaven National Laboratory Gamma Facility.

(b) The samples irradiated at room temperature and tested at 158 F were irradiated at the Materials Testing Reactor Gamma Facility. The radiation doses were slightly higher than those received by the samples irradiated at the Brookhaven National Laboratory Gamma Facility. Exposure doses at MTR were 0, 2.2×10^9 , 4.4×10^9 , 8.9×10^9 , and 1.3×10^{10} ergs g⁻¹ (C).

(c) Four dumbbells tested.

TABLE A-82. ELASTOMER CHANGE IN ELONGATION IN 1000
90 MEGARADS(a)(142)

Elastomer	Per Cent Change
High phenyl silicone(b)	1.8
Natural rubber(c)	-12
Brominated isobutylene-isoprene	-12.8
Isocyanate urethane	-30
Acrylonitrile-styrene	-36
Polyvinyl chloride	-44
Ethylene	-50
Butadiene acrylonitrile	-55
LS-53 silicone	-78
Neoprene	-78
Methylvinyl silicone	-80
Natural rubber	-82
Vinylidene fluoride-hexafluoropropylene	-84
Dimethyl silicone	-90

(a) 9×10^5 ergs g⁻¹, absorbed dose.

(b) No antirad additives in silicone formulations.

(c) Includes special antirad.

TABLE A-83. GAMMA RADIATION-INDUCED CHANGES IN SILICONE ELASTOMERS
WITH VARYING FILLER LOADINGS AND POSTCURES⁽¹⁰⁰⁾

Materials	Original Properties			Properties After Exposure to 1×10^8 Roentgens (8.7×10^9 Ergs G ⁻¹ (C))		
	Hardness,	Tensile,	Elongation,	Hardness,	Tensile,	Elongation,
	Shore A	psi	%	Shore A	psi	%
<u>Filler-Loading Series</u>						
K-1046R	65	855	290	93	1035	30
K-1047R B-3	76	880	230	96	1155	25
K-1048R	79	875	215	97	1150	25
<u>Postcure Series</u>						
K-1047R B-4	54	1020	620	94	1085	40
K-1047R B-5	64	965	400	94	980	40
K-1047R B-6	67	940	375	94	1185	40
K-1047R B-2	66	820	285	94	985	55

TABLE A-81. EFFECT OF GAMMA RADIATION ON THE MECHANICAL PROPERTIES OF FLUOROELASTOMERS (13)

Material	Exposure Dose		Initial Properties and Per Cent Change						Remarks
	Ergs G ⁻¹ (C) x 10 ⁻⁹	Roentgen x 10 ⁻⁶	Hardness		Elongation		Tensile Strength		
			Shore A	Δ%	Per Cent	Δ%	PSI	Δ%	
Fluorocarbon Elastomers									
Viton A-12	0	0	58		365		1245		Tan
	8.7	100		44.8		-86.3		0.0	Very slightly tacky, broke when bent 180°
Viton A-13	0	0	67		340		2100		Black
	8.7	100		32.8		-92.6		16.4	Very slightly tacky, broke when bent 180°
Viton A-14	0	0	75		260		1975		Black
	8.7	100		24.0		-84.6		-8.4	Very slightly tacky, broke when bent 180°
Viton A-15	0	0	84		200		1720		Black
	8.7	100		15.6		-85.0		2.6	Very slightly tacky, broke when bent 180°
Viton A-16	0	0	67		800		1285		Black
	8.7	100		28.9		-93.0		38.4	Slightly tacky, broke when bent 180°
Viton A-17	0	0	68		420		1980		Black
	8.7	100		26.8		-88.1		-3.6	Slightly tacky, broke when bent 180°
Viton A-18	0	0	60		325		2205		Black
	8.7	100		20.1		-84.0		-10.0	Slightly tacky, broke when bent 180°
Fluorinated Polyester Elastomer									
Hooker HA-1	0	0	68		225		1830		Black
	0.44	5		2.9		-16.6		-26.0	
	1.9	22		4.4		-51.1		-55.0	
	4.8	56		14.7		-68.0		-69.6	
	8.7	100		17.6		-82.2		-64.7	
	26	300		29.4		-93.3		-74.7	Broke when bent 180°
	44	500		39.7		-95.6		-36.2	Broke when bent 180°
Hooker HA-2	0	0	80		110		1460		Black
	0.44	5		6.3		4.5		-11.2	
	1.9	22		7.5		-18.2		-12.0	
	4.8	56		12.5		-54.5		-35.0	
	8.7	100		13.8		-77.2		-39.9	
	26	300		21.3		-90.9		-43.7	Broke when bent 180°
	44	500		23.8		-95.5		-64.1	Broke when bent 180°

TABLE A-85. RECIPES FOR FLUOROELASTOMERS TESTED FOR RADIATION STABILITY (127)

Material, parts by weight	Viton A-12	Viton A-13	Viton A-14	Viton A-15
Viton A	100.0	100.0	100.0	100.0
Zinc Oxide	10.0	10.0	10.0	10.0
Dyphos	10.0	10.0	10.0	10.0
Thermax	--	20.0	40.0	60.0
HMDA-Carbamate	1.0	1.0	1.0	1.0
		Viton A-16	Viton A-17	Viton A-18
Viton A		100.00	100.0	100.00
Darlington 601 MgO		15.00	15.0	15.00
Thermax		20.00	20.0	20.00
HMDA-Carbamate		0.75	1.0	1.25
			Hooker HA-1	Hooker HA-2
Adipate			100.0	--
Adipate-isophthalate			--	100.0
SRB Black			50.0	50.0
Parceal U			20.0	20.0
DiCap 400			19.0	19.0

Note: Viton A compounds were cured 30 minutes at 300 F and postcured 24 hours at 400 F. Hooker compounds were cured 55 minutes at 320 F and postcured 16 hours at 350 F.

TABLE A-86. EFFECTS OF RADIATION ON POLY-ALPHA-METHYLSTYRENE (175)

Exposure Dose, ergs g ⁻¹ (C)	Absorbed Dose, (ev g ⁻¹ x 10 ⁻²⁰)	\bar{M}_n (a) x 10 ⁻⁵	\bar{M}_w (b) x 10 ⁻⁵	Average Number of Chain Scissions Per Molecule			Number of Chain Scissions Per Gram x 10 ⁻¹⁷
				Weak Bonds Broken	Normal Bonds Broken	Total Bonds Broken	
0	0	1.90	2.10	--	--	--	--
1.1 x 10 ⁸	0.7(c)	1.67	2.04	0.12	0.02	0.14	4.4
2.1 x 10 ⁸	1.3(c)	1.53	1.98	0.20	0.04	0.24	7.8
4.2 x 10 ⁸	2.6(c)	1.42	1.94	0.30	0.04	0.34	10.8
9.1 x 10 ⁸	5.7(c)	1.30	1.75	0.38	0.08	0.46	14.7
1.1 x 10 ⁹	7.2(c)	1.20	1.65	0.39	0.19	0.58	18.6
1.4 x 10 ⁹	8.8(c)	1.18	1.58	0.40	0.21	0.61	19.5
0	0	2.60	2.90	--	--	--	--
2.6 x 10 ⁸	1.6(d)	2.15	2.76	0.22	0.00	0.22	4.8
4.0 x 10 ⁸	2.5(d)	1.95	2.65	0.30	0.03	0.33	7.8
5.6 x 10 ⁸	3.5(d)	1.88	2.53	0.34	0.04	0.38	8.9
7.7 x 10 ⁸	4.8(d)	1.60	2.40	0.37	0.25	0.62	14.5
9.6 x 10 ⁸	6.0(c, d)	1.50	2.23	0.38	0.35	0.73	17.1
1.5 x 10 ⁹	9.3(c, d)	1.44	2.01	0.40	0.40	0.80	18.7
1.6 x 10 ⁹	9.9(c)	1.55	2.49	0.40	0.28	0.68	15.8
2.2 x 10 ⁹	13.7(c)	1.12	1.65	0.40	0.98	1.32	30.8
2.6 x 10 ⁹	16.4(c)	0.99	1.50	0.40	1.22	1.62	37.9
2.8 x 10 ⁹	17.5(c)	1.16	1.82	0.40	0.84	1.24	28.9
3.4 x 10 ⁹	21.3(d)	1.00	1.53	0.40	1.20	1.60	37.3

(a) \bar{M}_n = number-average molecular weight calculated from osmotic pressure.(b) \bar{M}_w = weight-average molecular weight calculated from viscosity measurements.(c) Dose rate = 3.6×10^{19} ev g⁻¹ hr⁻¹, 5.6×10^7 ergs g⁻¹ (C) hr⁻¹.(d) Dose rate = 9.2×10^{19} ev g⁻¹ hr⁻¹, 3.6×10^7 ergs g⁻¹ (C) hr⁻¹.

Gases Evolved During Irradiation of Poly-Alpha-Methylstyrene* (188)

Product	Per Cent by Volume*
Hydrogen	58
Methane	5.2
Water	0.8
Carbon monoxide	1.8
Oxygen	0.03
Carbon dioxide	2.1
Isobutane	0.4
Isobutene	0.5
1-Butene	0.5
2-Butene	4.2
Benzene	26
Toluene	0.05
Isopropyl benzene	0.05
Alpha-Methylstyrene	0.3

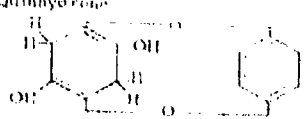
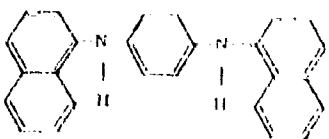
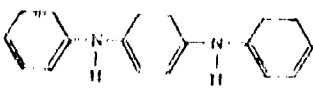
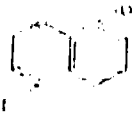
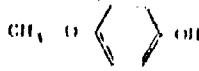
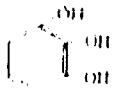

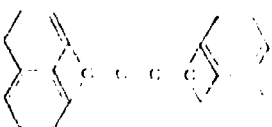
*14-g sample; absorbed dose, 23×10^{20} ev g⁻¹.*Estimated reliability ± 10 per cent.

TABLE A-87. COMPARISON OF TENSILE STRENGTH OF FIBERS⁽⁵¹⁾

Additive(a), weight per cent	Exposure Dose, ergs g ⁻¹ (C)			
	8.39×10^7	4.20×10^8	8.39×10^8	1.78×10^9
<u>Polymer A</u>				
--	--	0.98	0.84	0.96
1.0N	--	0.86	0.85	0.67
0.5P	0.96	0.91	0.85	0.82
1.0P	0.93	1.01	--	0.90
1.0Q	--	0.89	0.88	0.77
1.0S	1.08	0.99	0.81	0.83
1.0S-2.0X	1.03	1.03	1.17	0.94
1.0T	0.98	1.83	0.69	0.77
1.0U	0.93	0.94	0.84	0.79
1.0V	0.92	0.88	0.83	0.67
0.5W	--	1.09	0.94	0.86
1.0W	0.95	0.90	0.79	0.70
5.0W	1.03	0.89	0.84	0.81
1.0X	--	0.98	0.87	0.83
1.0Y	0.94	1.79	0.80	0.76
<u>Polymer B</u>				
--	1.03	1.02	0.88	0.77
1.0M	--	0.98	--	0.76
1.0N	1.02	1.06	0.92	0.91
0.5P	0.88	0.91	0.91	0.83
1.0P	--	1.00	0.91	0.90
5.0P	--	0.23	--	0.16
0.5Q	1.08	1.05	1.04	0.96
1.0Q	1.20	0.77	0.70	0.73
1.0R	--	1.06	--	0.80
1.0S	1.05	0.93	0.94	0.80
20.0S	--	0.52	--	0.37
1.0T	1.08	0.76	0.73	0.71
1.0U	1.08	1.04	0.83	0.91
0.5V	--	1.02	0.93	0.86
1.0V	1.09	1.10	0.98	0.95
5.0V	1.18	1.20	1.12	1.06
1.0W	--	1.06	--	0.91
5.0W	--	1.17	1.14	1.08
1.0X	1.11	1.09	0.99	0.89
1.0Y	1.15	1.09	0.94	0.88
1.0Z	--	0.95	--	0.87

(a) See Table A-36 for additives used.

TABLE A-90. CODING OF ADDITIVES USED IN THE STUDY(51)

Code	Additive	Remarks
M	Polymerized activated carbon	Free radical captor
N	Quinhydrone 	One of the best antioxidants for rubber
P	N, N'-Di-2-naphthyl-p-phenylene diamine 	Antioxidant and antirad for rubber
Q	N, N'-Diphenyl-p-phenylene diamine 	Antioxidant and antirad for rubber
R	Lead nitrate	Heavy metal
S	Silver nitrate	Heavy metal
T	Cadmium nitrate	Good neutron captor
U	Barium nitrate	Radio opaque metal
V	1,5-Dihydroxy naphthalene 	Antioxidant, antirad
W	p-Methoxy phenol 	Antioxidant
X	Pyrogallol 	Antioxidant, antirad
Y	Congo red 	Abundant aromaticity
Z	Tetra-phenyl-butadiene 	Abundant aromaticity

APPENDIX W

GRAPHICAL DATA

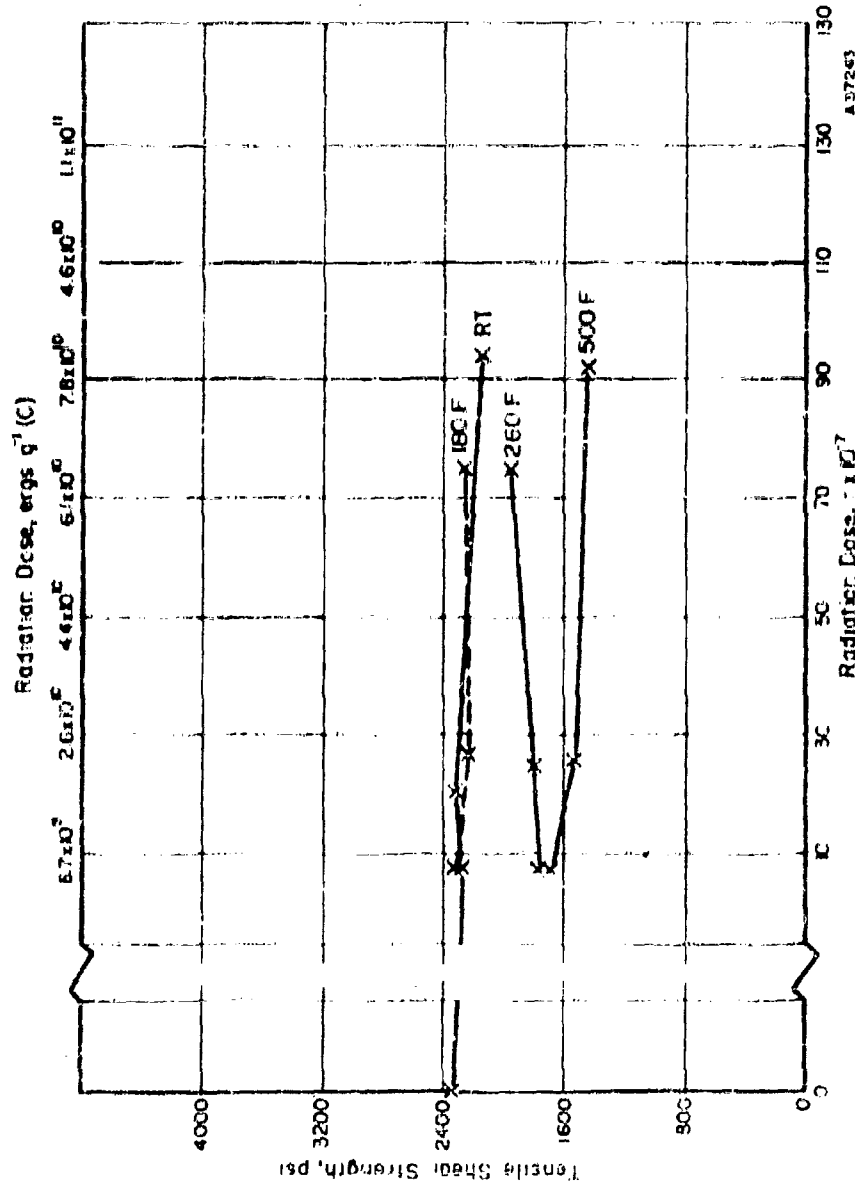


FIGURE B-1. EFFECT OF 75 F IRRADIATION ON TENSILE SHEAR STRENGTH OF EPOXY-PHENOLIC ADHESIVE 422. TESTED AT 75, 180, 260, AND 500 F(10)

Composition:

Epon 1001	35 parts	Aluminum dust	100 parts	Cure:	330 F, 30 min, 10 psi. (3)
Polyphen 5023	67 parts	Copper 8-quinolinate	5 part		
Dicyandiamide	6 parts	(Supplied as tape on 112 glass fabric with Volan A finish)			

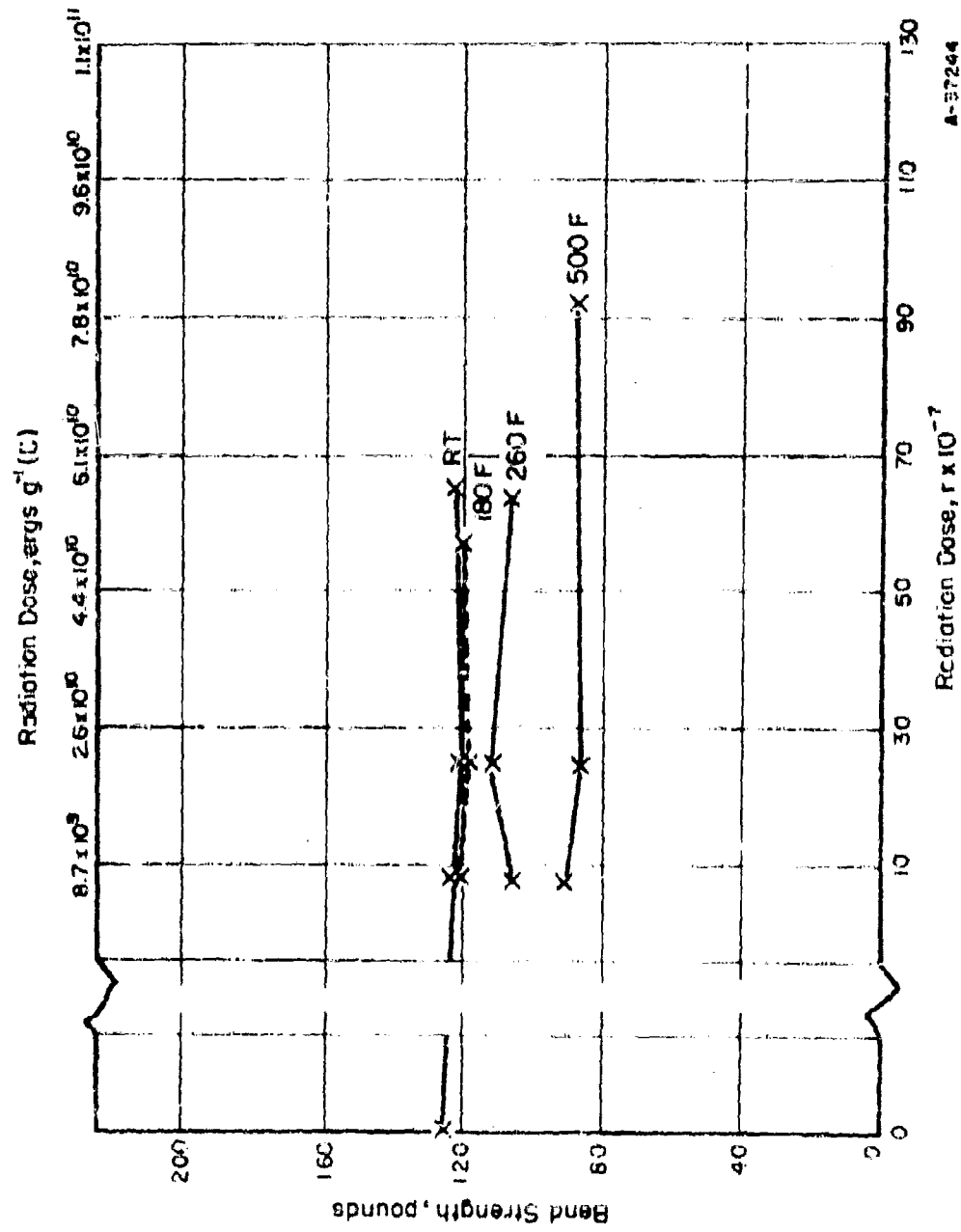


FIGURE E-2. EFFECT OF 75 F IRRADIATION ON BEND STRENGTH OF EPOXY-PHENOLIC ADHESIVE
422J TESTED AT 75, 180, 260, AND 500 F (10)

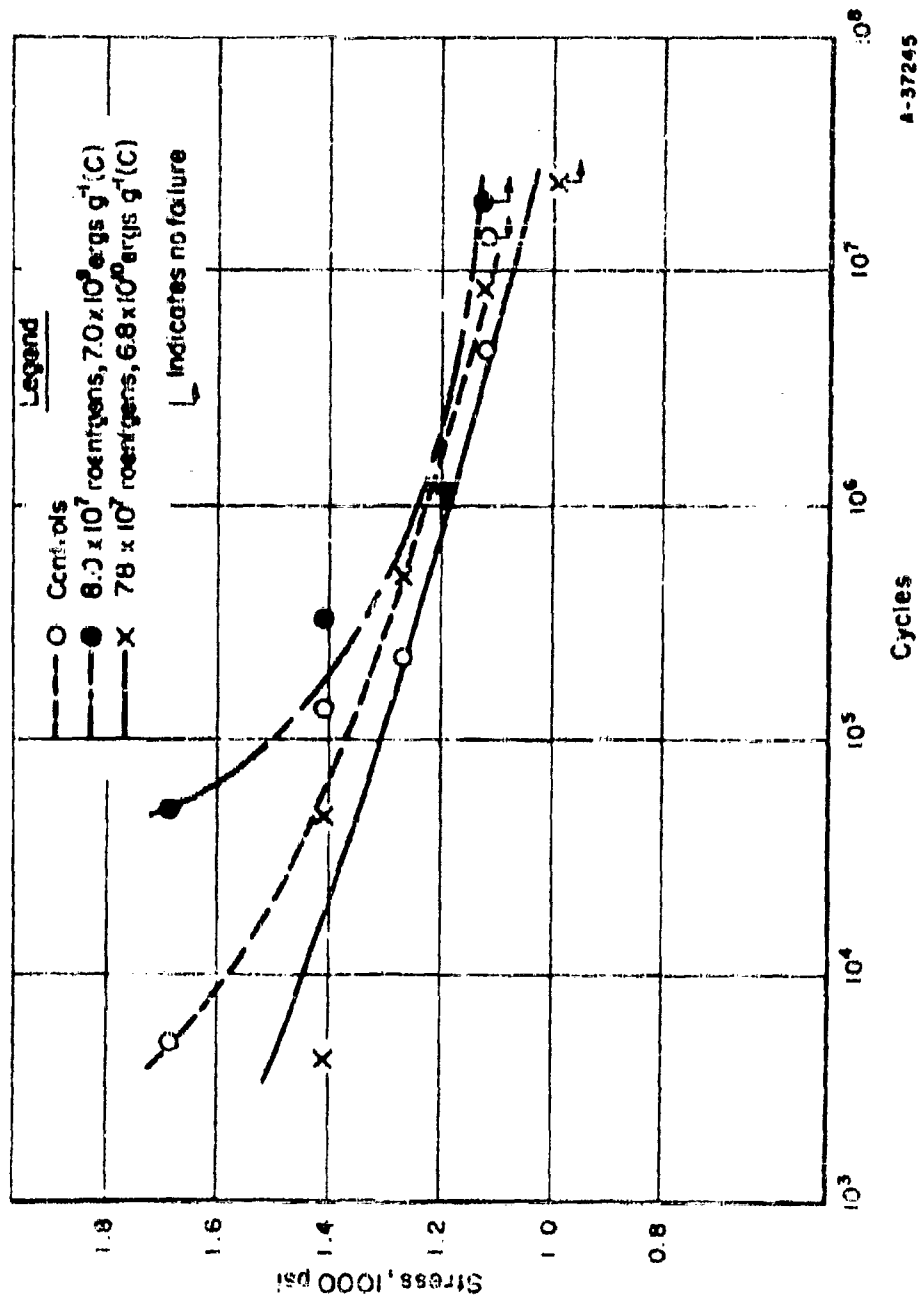


FIGURE B-3. EFFECT OF 75 F IRRADIATION ON FATIGUE RESISTANCE OF EPOXY-PHENOLIC ADHESIVE
422J TESTED AT 75 F(13)

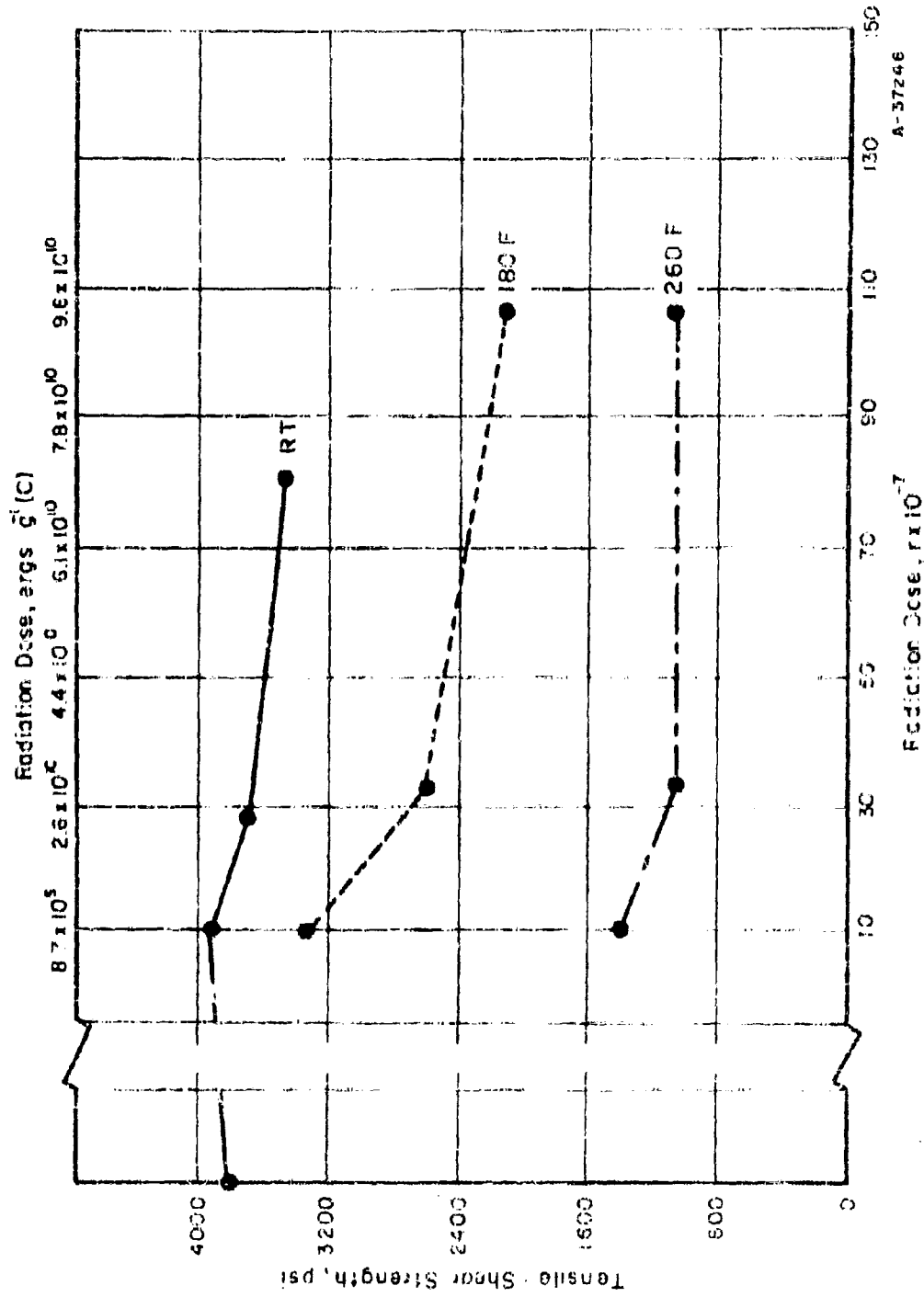


FIGURE B-4. EFFECT OF 75 F IRRADIATION ON TENSILE-SHEAR STRENGTH OF VINYL-PHENOLIC ADHESIVE FM-47 TESTED AT RT, 180, AND 260 F (10)

Cure: 300 F, 25 min, 200 psi (10)

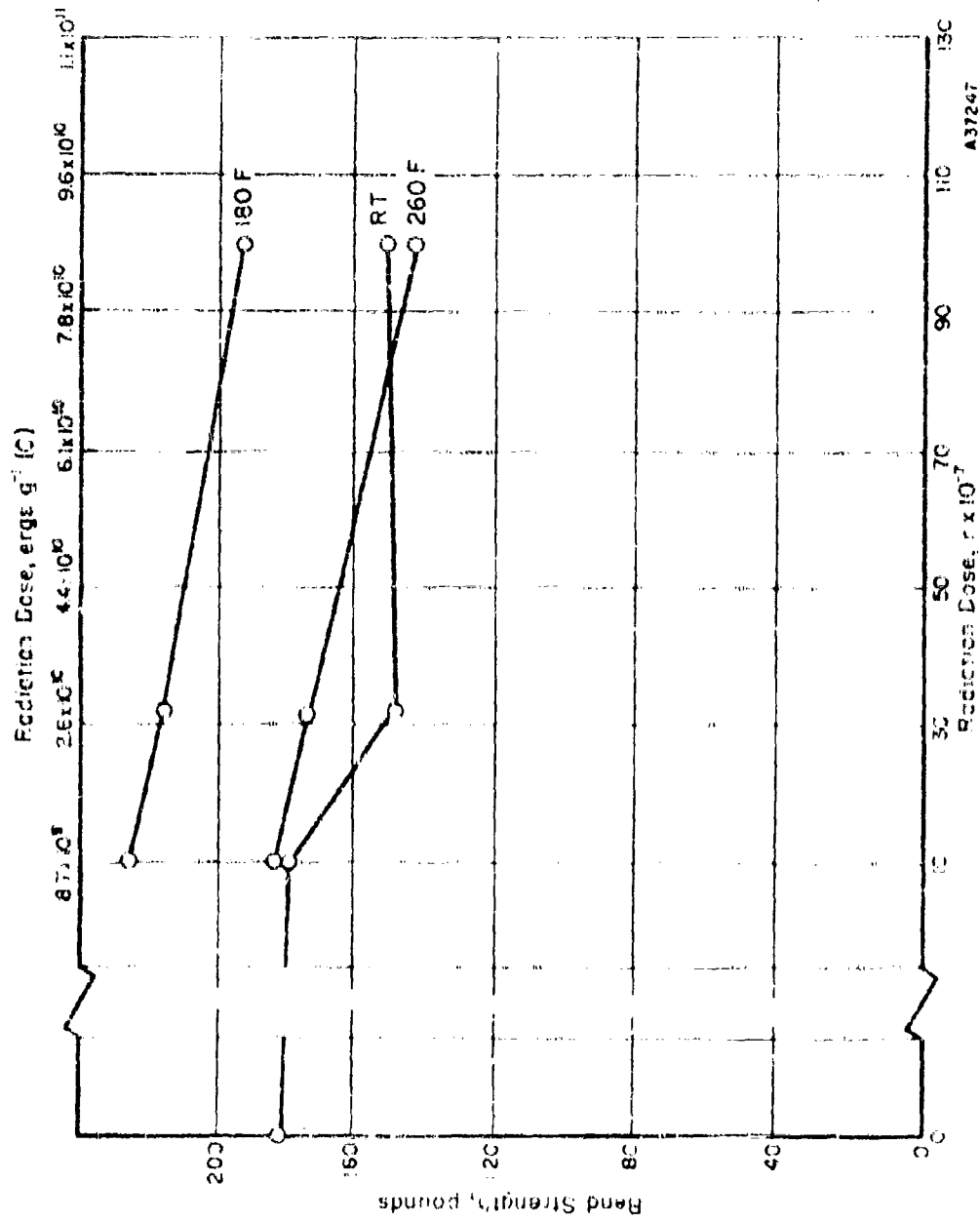


FIGURE B-5. EFFECT OF 75 F IRRADIATION ON BEND STRENGTH OF VINYL-PHENOLIC ADHESIVE FM-47 TESTED AT 15, 180, AND 260 F(10)

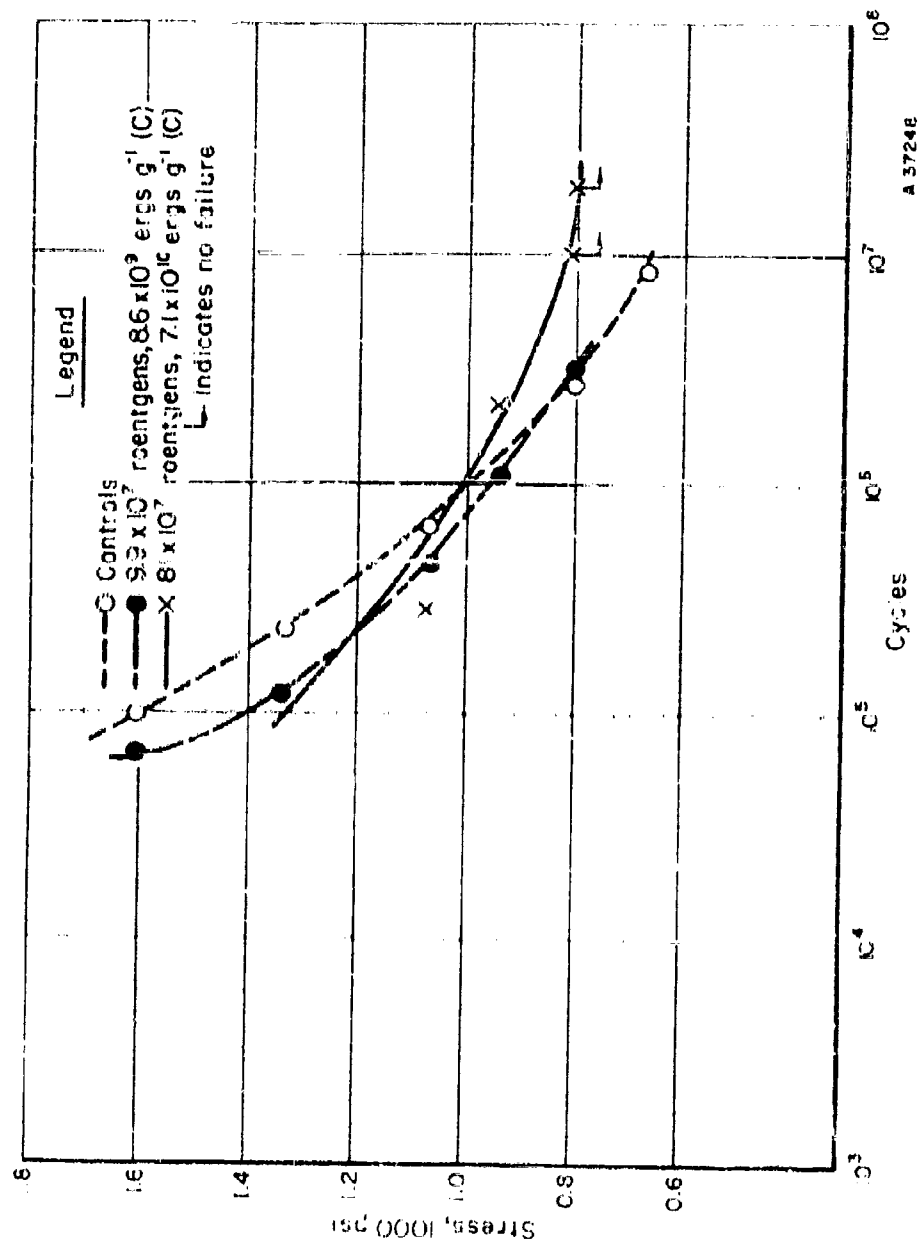


FIGURE B-1. EFFECT OF 75 F IRRADIATION ON FATIGUE RESISTANCE OF VINYL-PHENOLIC ADHESIVE FM-47 TESTED AT 75 F (10)

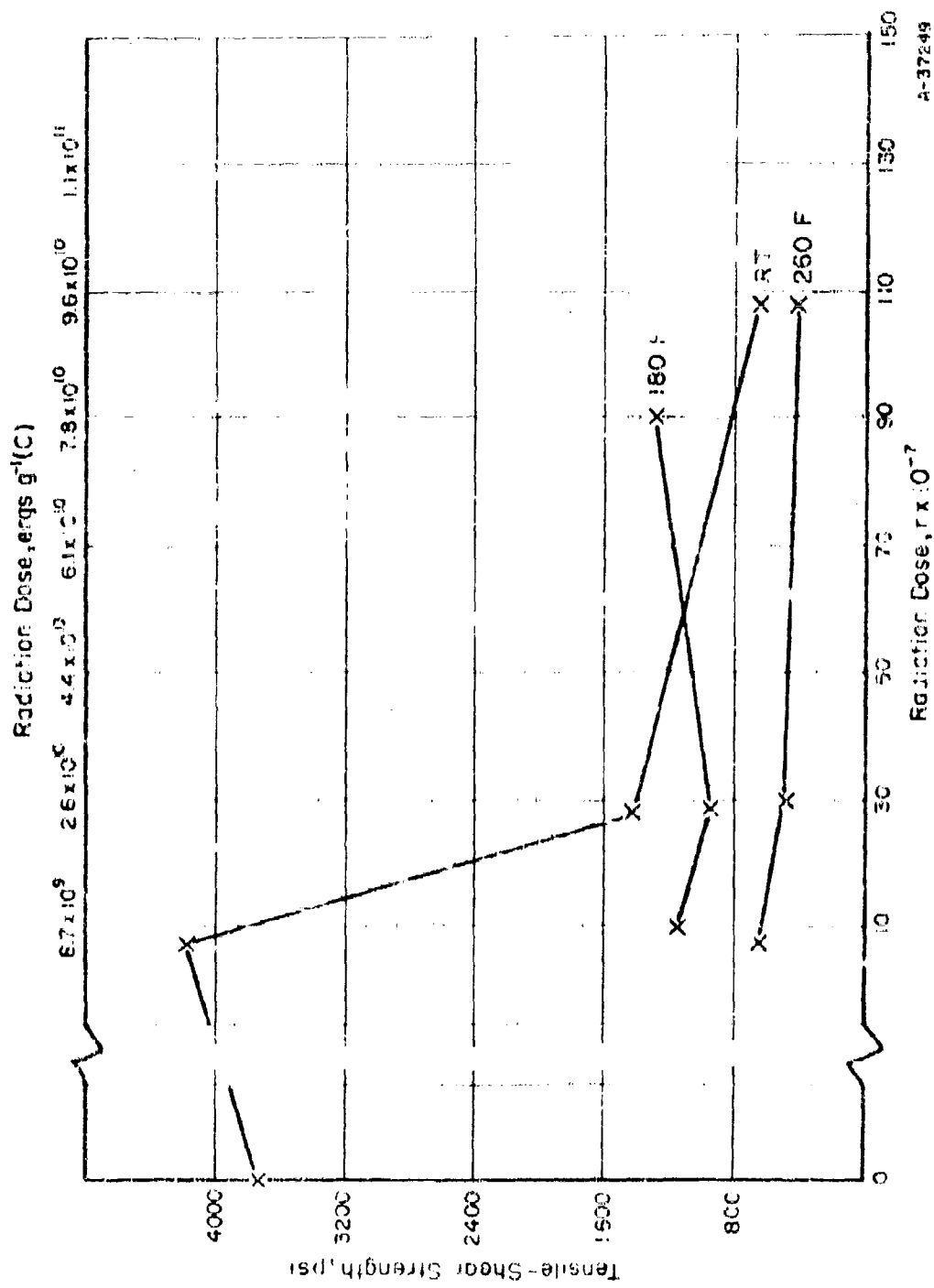


FIGURE B-7 EFFECT OF 75 F IRRADIATION ON TENSILE-SHEAR STRENGTH OF VINYL-PHENOLIC ADHESIVE CYCLEWELD 55-9 TESTED AT 75, 180, AND 260 F(10)

A-37249

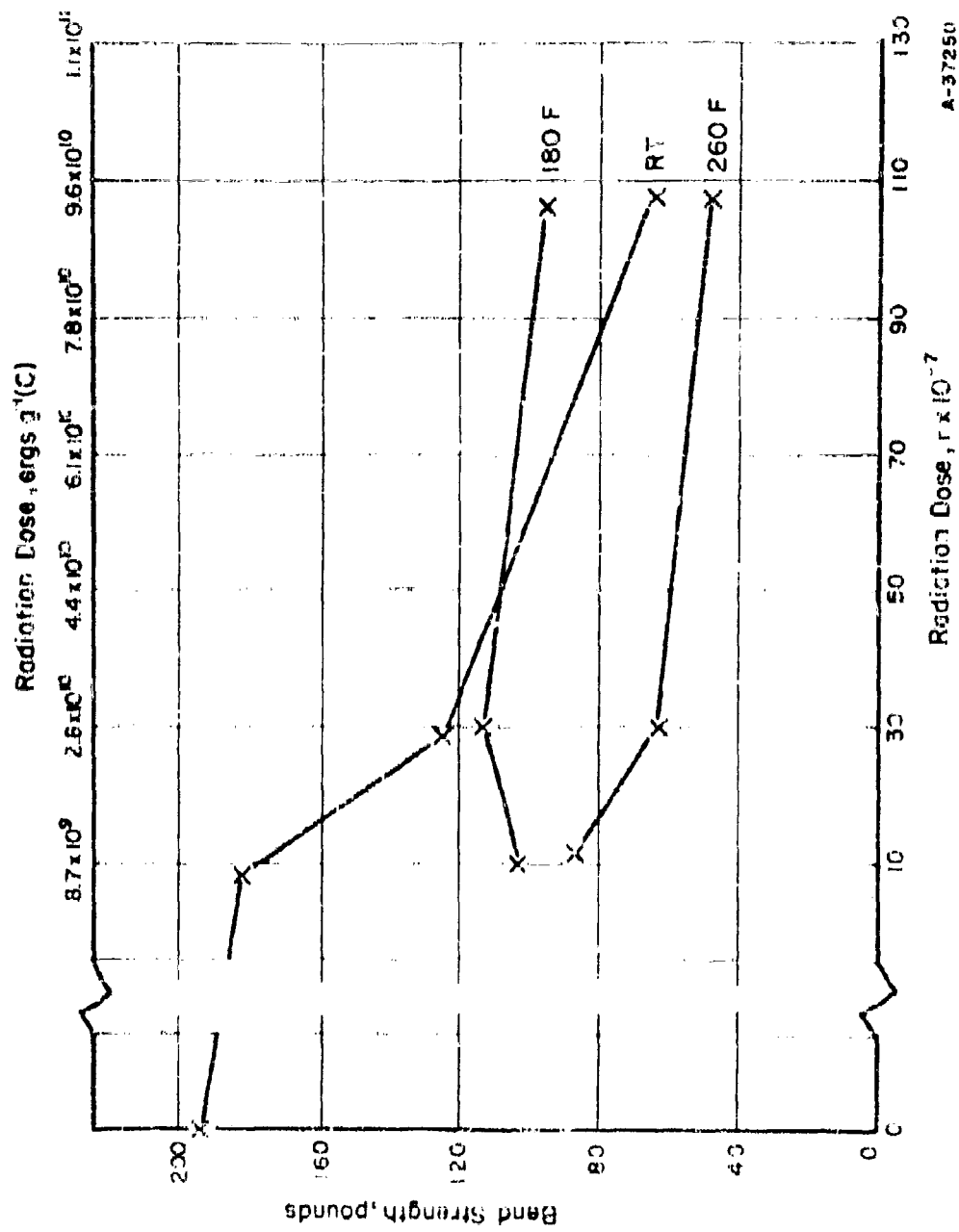


FIGURE B-8. EFFECT OF 75 F IRRADIATION ON BEND STRENGTH OF VINYL-PHENOLIC ADHESIVE CYCLED WELD 55-9 TESTED AT 180, 180, AND 260 F(10)

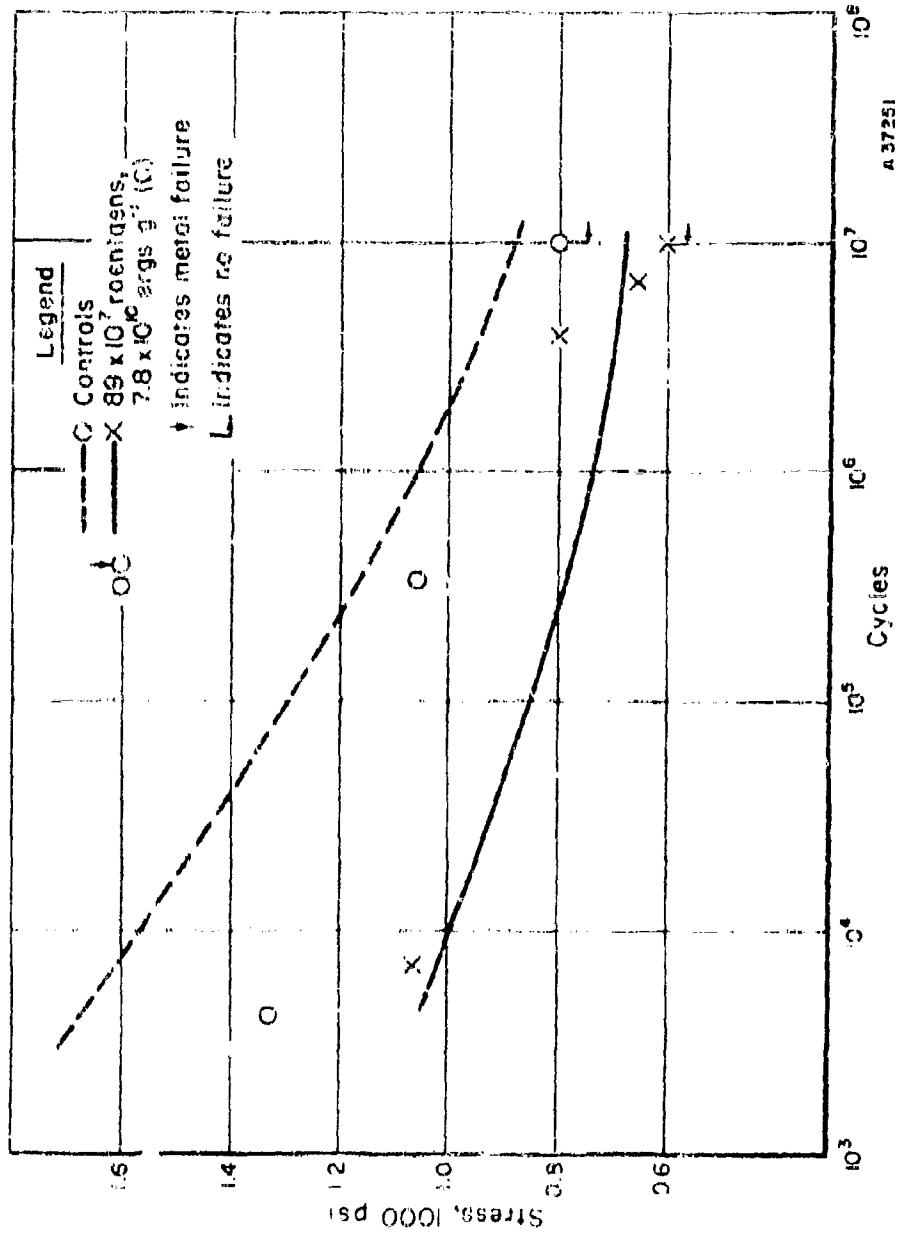


FIGURE B-9. EFFECT OF 75 F IRRADIATION ON FATIGUE RESISTANCE OF VINYL-PHENOLIC ADHESIVE CYCLEWELD 55-9 TESTED AT 75 F(19)

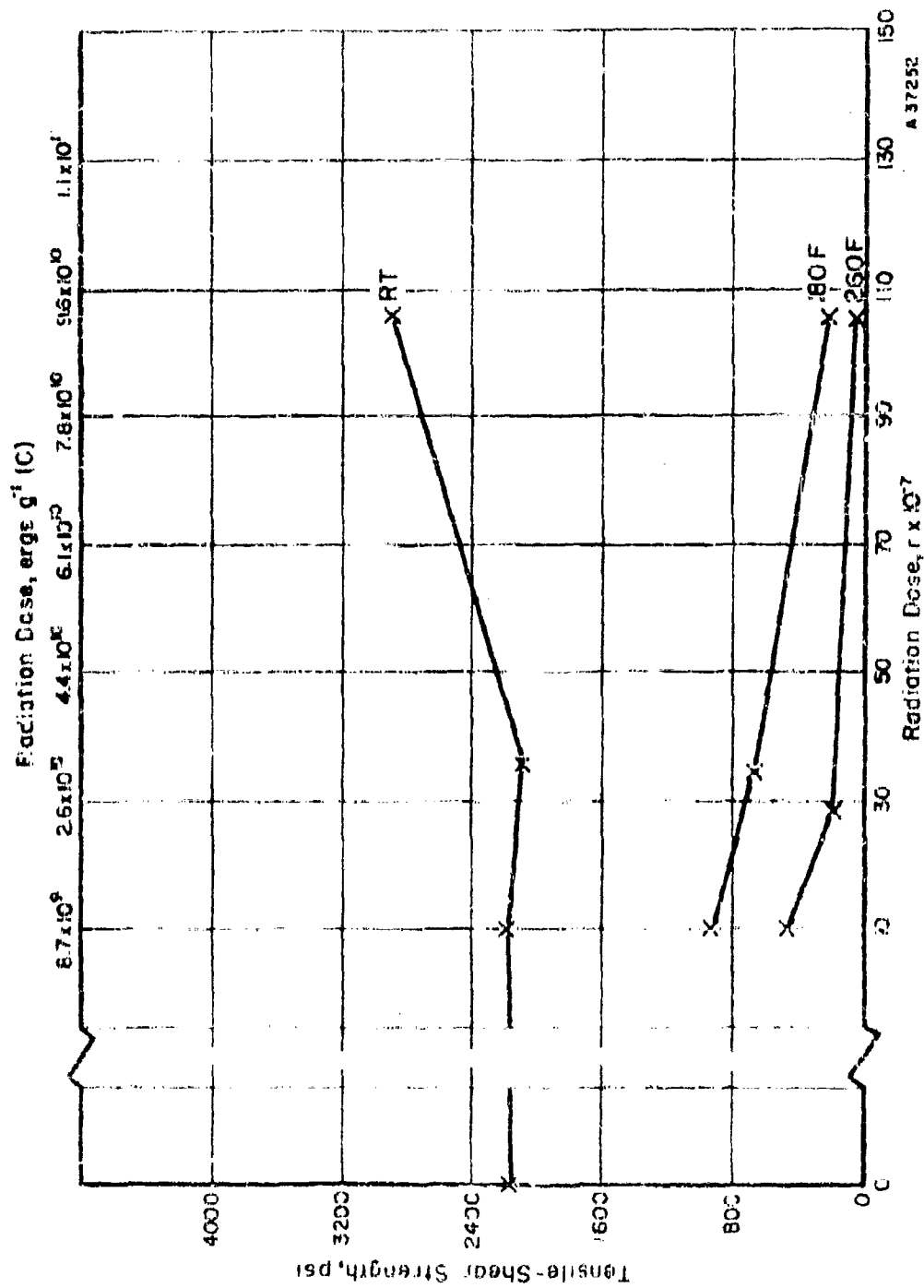


FIGURE B-10. EFFECT OF 75 F IRRADIATION ON TENSILE-SHEAR STRENGTH OF MODIFIED NYLON-PHENOLIC ADHESIVE CYCLEWELD C-6 TESTED AT 75, 180, AND 260 F(10)

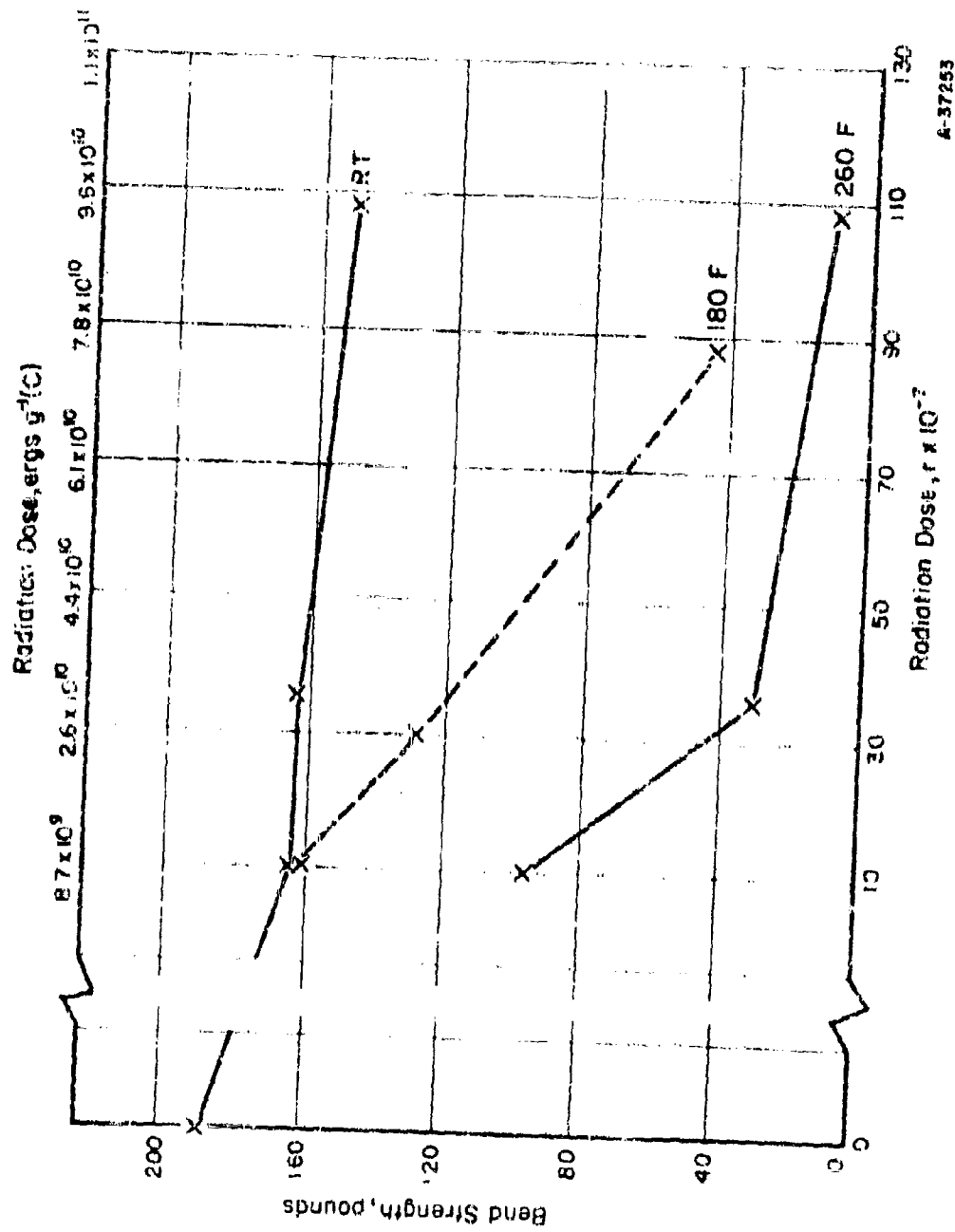


FIGURE B-10. EFFECT OF 75 F IRRADIATION ON BEND STRENGTH OF MODIFIED NYLON-PHENOLIC ADHESIVE CYCLEWELD C-6 TESTED AT 75, 180, AND 260 F(12)

A-37253

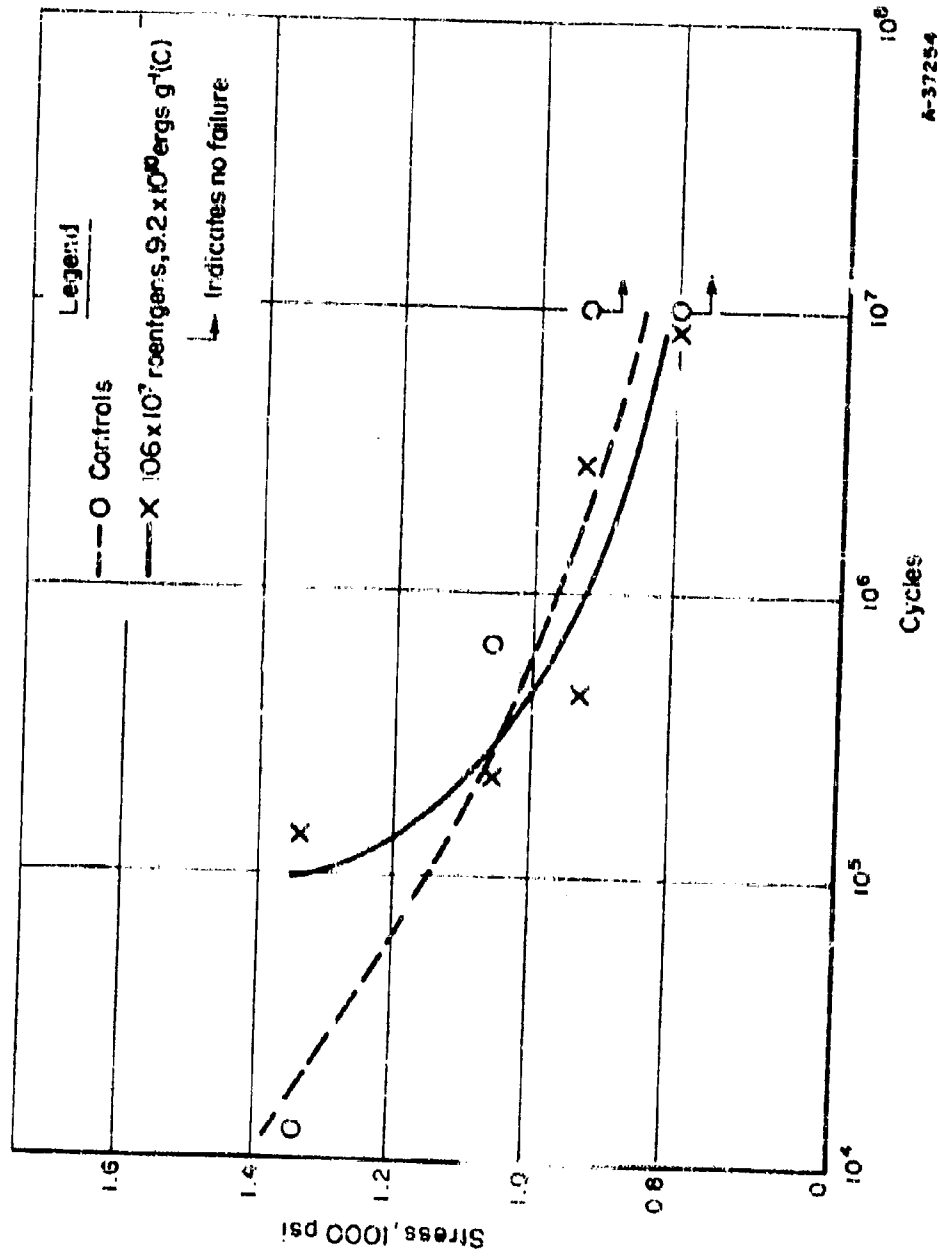


FIGURE B-12. EFFECT OF 75 F IRRADIATION ON FATIGUE RESISTANCE OF MODIFIED NYLON-PHENOLIC ADHESIVE CYCLEWELD C-6 TESTED AT 75 F (11)

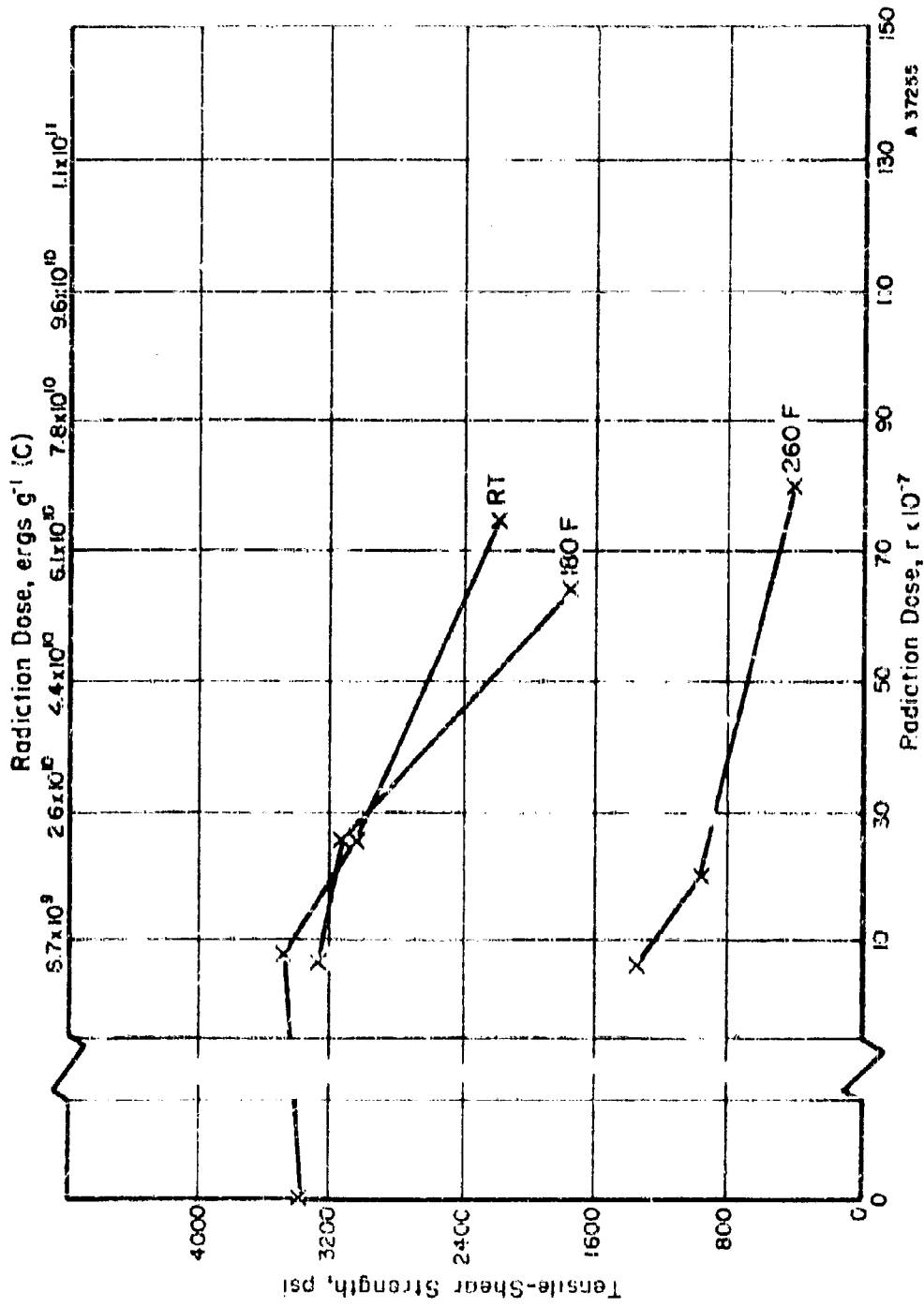


FIGURE B-13. EFFECT OF 75 F IRRADIATION ON TENSILE-SHEAR STRENGTH OF EPOXY ADHESIVE EPON VIII TESTED AT 75, 180, AND 260 F(10)

Cure: 200 F, 90 min. 10 psi. (3)

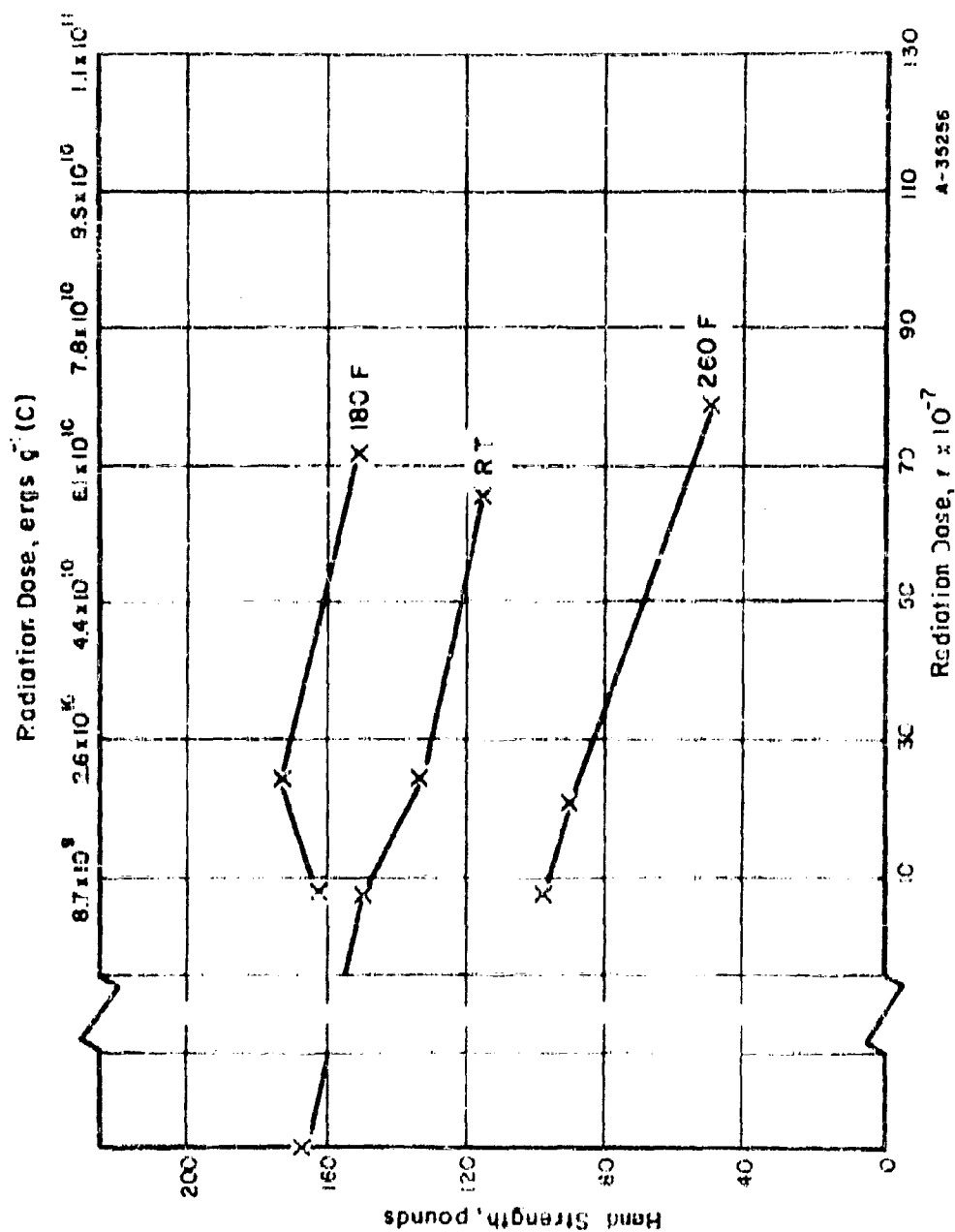


FIGURE B-14 EFFECT OF 75 F IRRADIATION ON BEND STRENGTH OF EPOXY ADHESIVE EPON VIII TESTED AT 15, 180, AND 260 F (10)

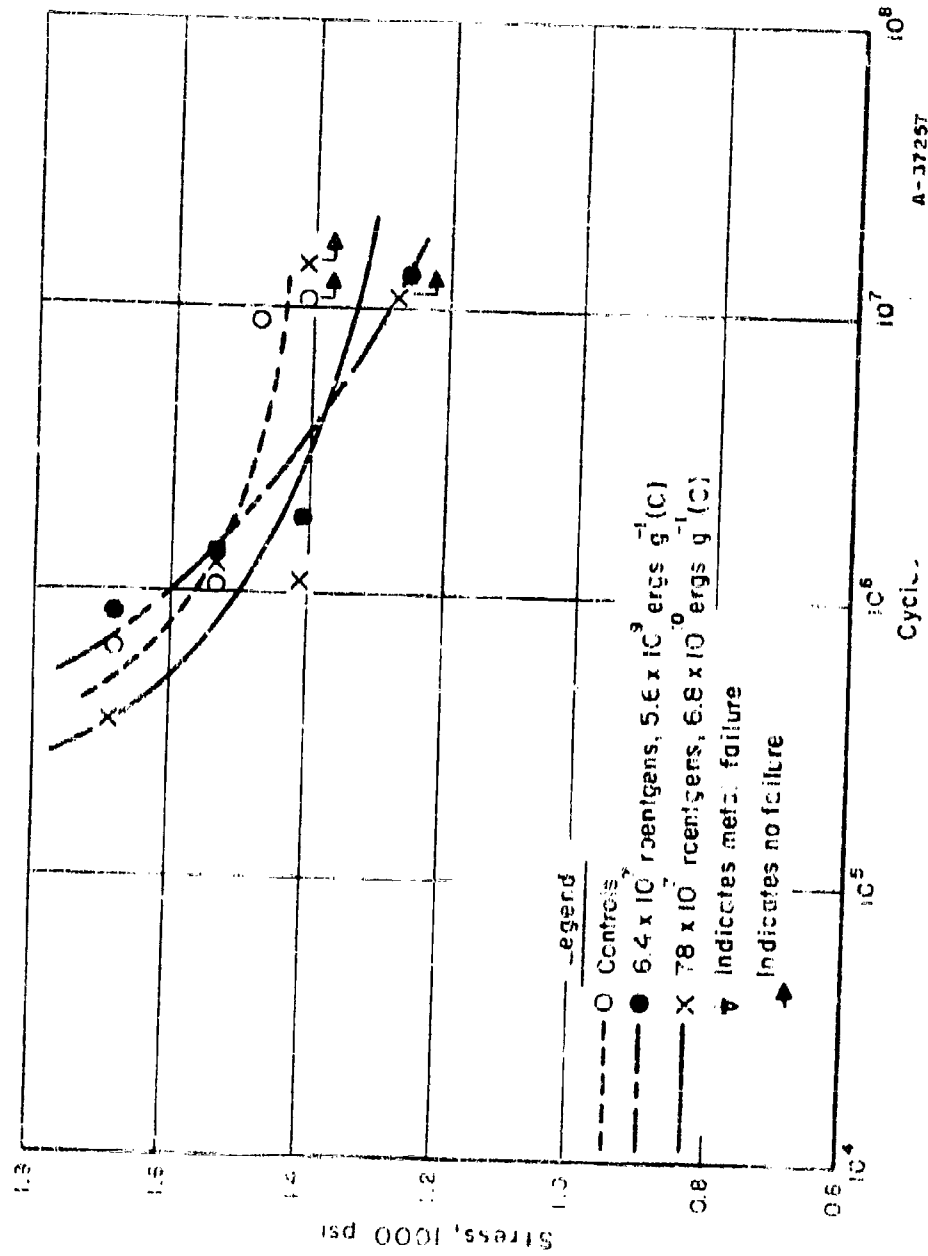


FIGURE E-15. EFFECT OF 75 F IRRADIATION ON FATIGUE RESISTANCE OF EPOXY ADHESIVE
EPON VIII TESTED AT 75 F (C)

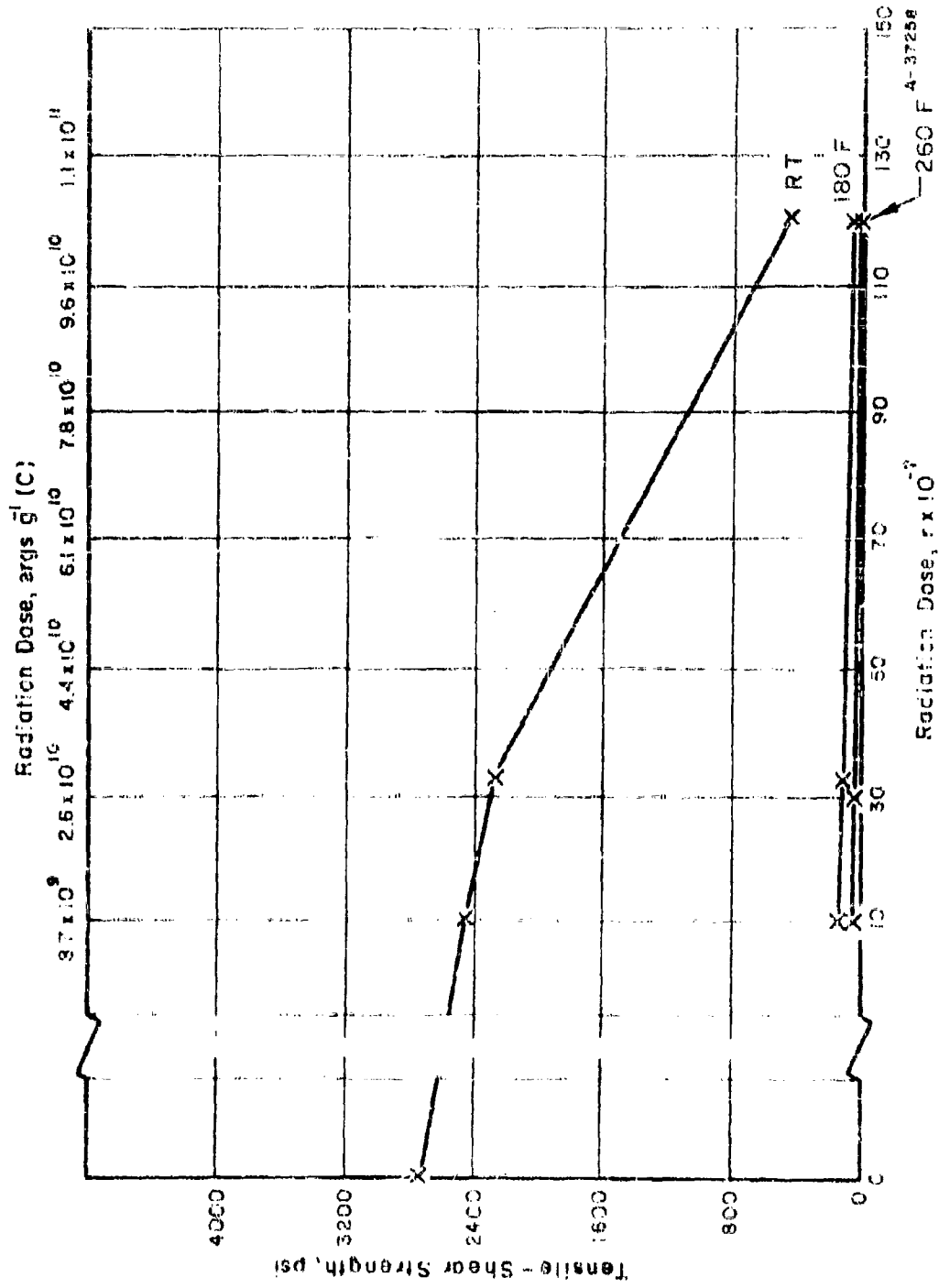


FIGURE B-16. EFFECT OF 75 F IRRADIATION ON TENSILE-SHEAR STRENGTH OF MODIFIED EPOXY ADHESIVE CYCLEWELD C-14 TESTED AT 75, 180, AND 260 F(10)

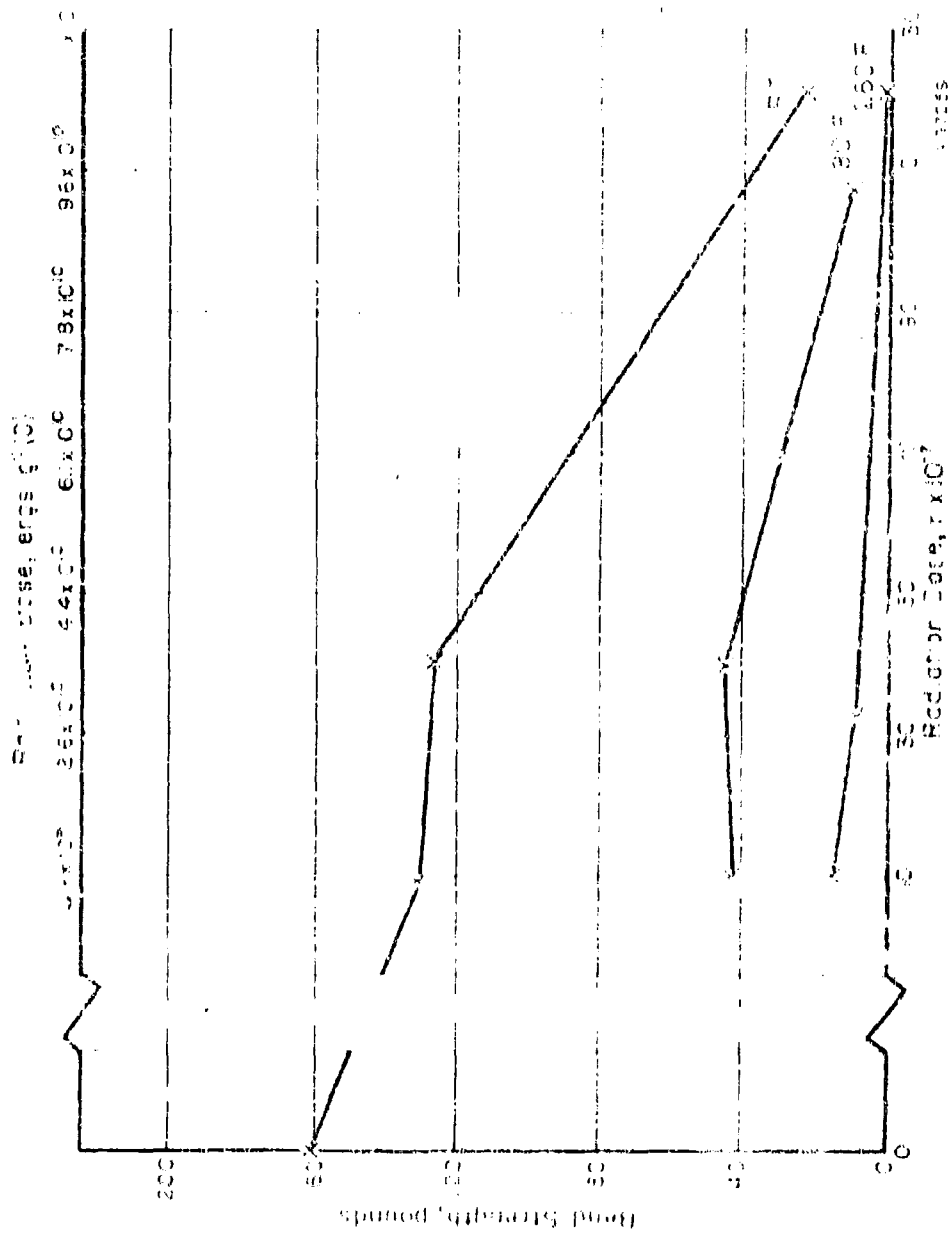


FIGURE B-17. EFFECT OF γ RADIATION ON BOND STRENGTH OF MODIFIED EPOXY ADHESIVE CYCLED 0 C-14 TESTED AT 75, 180, AND 260 F(10)

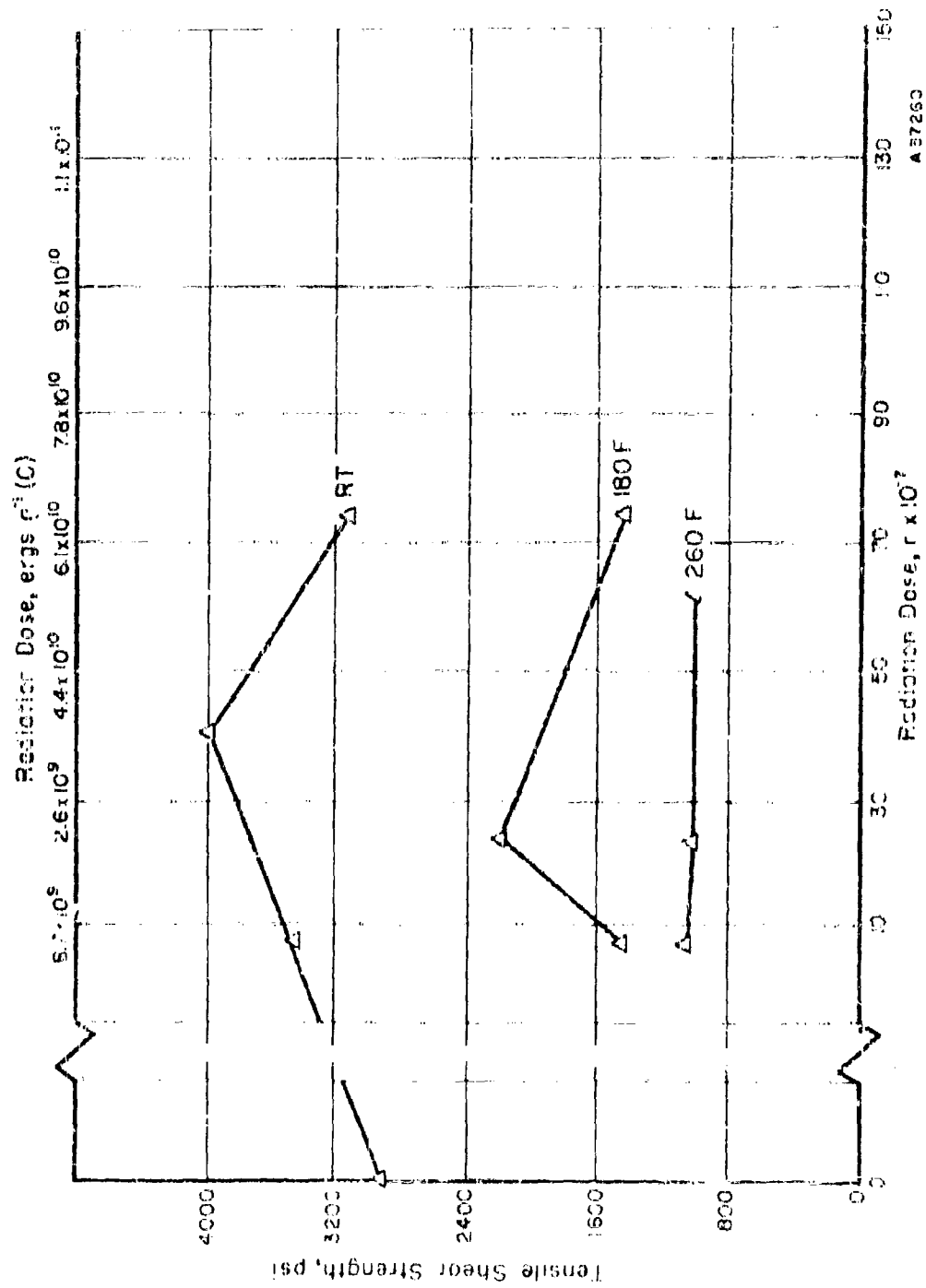


FIGURE B-18. EFFECT OF 75 F IRRADIATION ON TENSILE-SHEAR STRENGTH OF NITRILE RUBBER-PHENOLIC ADHESIVE SCOTCHBOND AF-3 TESTED AT 75, 180, AND 260 F (10)

Cure: 325 F, 60 min., 150 psi (10)

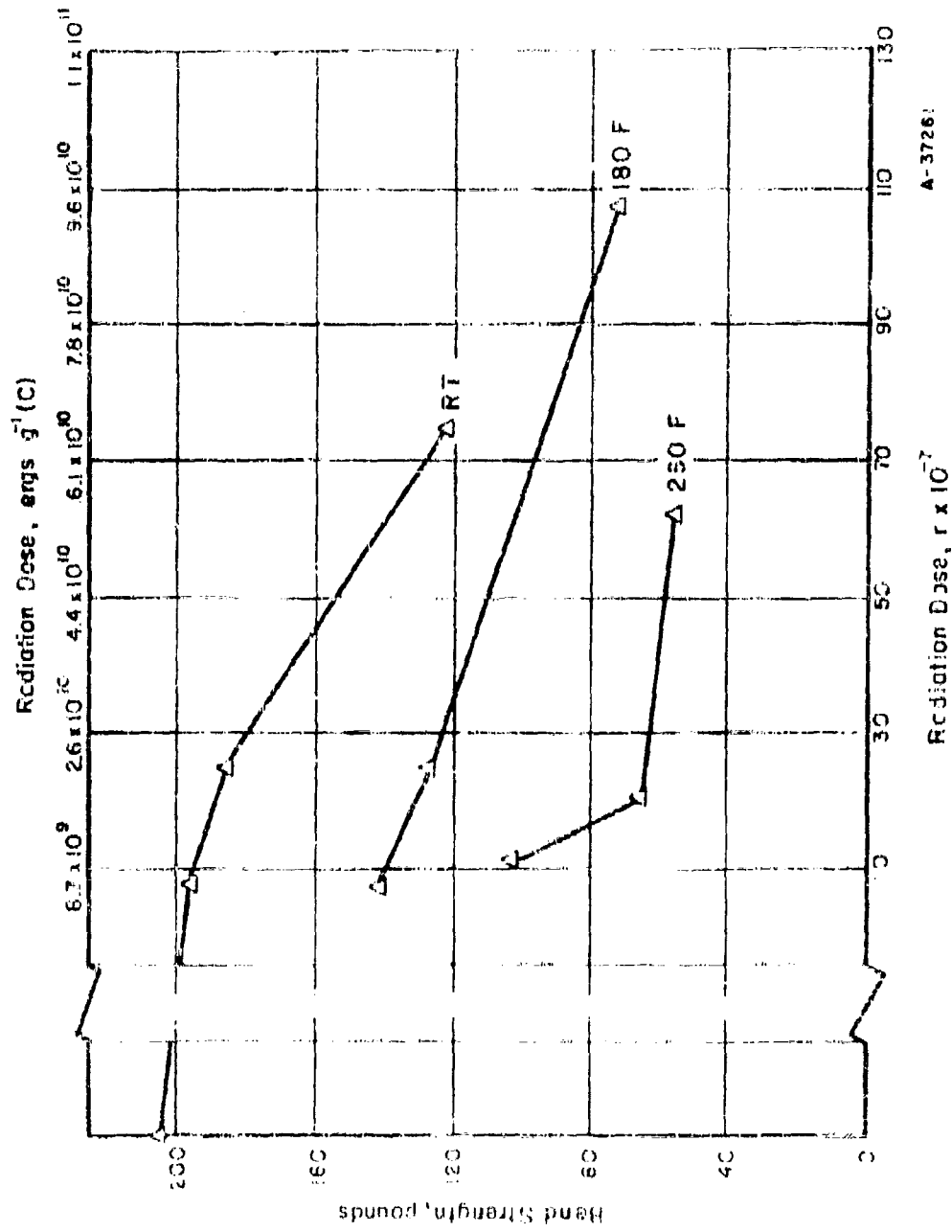


FIGURE 5-19. EFFECT OF 75 F IRRADIATION ON BEND STRENGTH OF NITRILE RUBBER-PHENOLIC ADHESIVE SCOTCHWELD AF-6 TESTED AT 75, 180, AND 260 F (10)

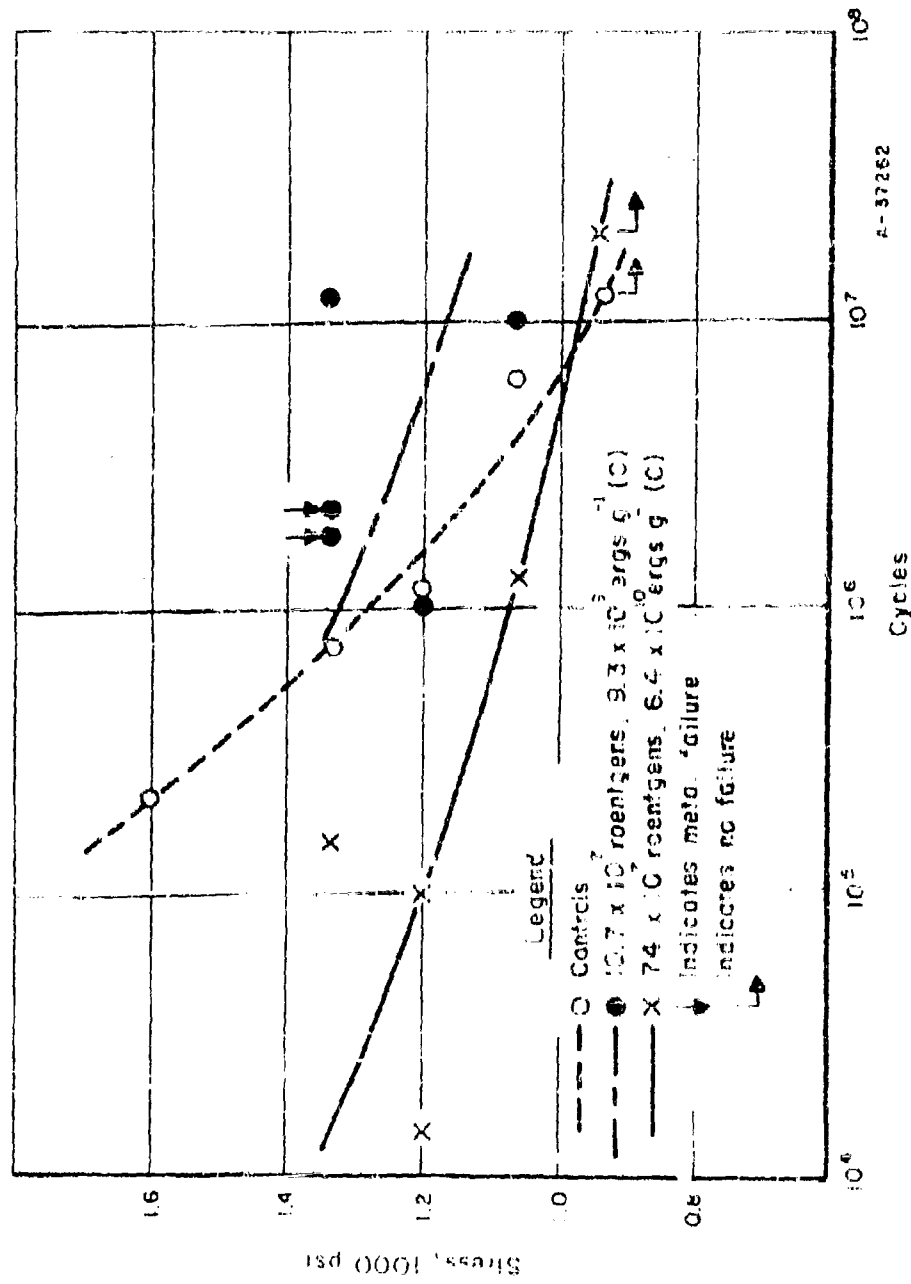


FIGURE B-10. EFFECT OF 15 F IRRADIATION ON FATIGUE RESISTANCE OF NITRILE RUBBER-PHENOLIC ADHESIVE SCOTCHWELD AF-6 TESTED AT 75 F (10)

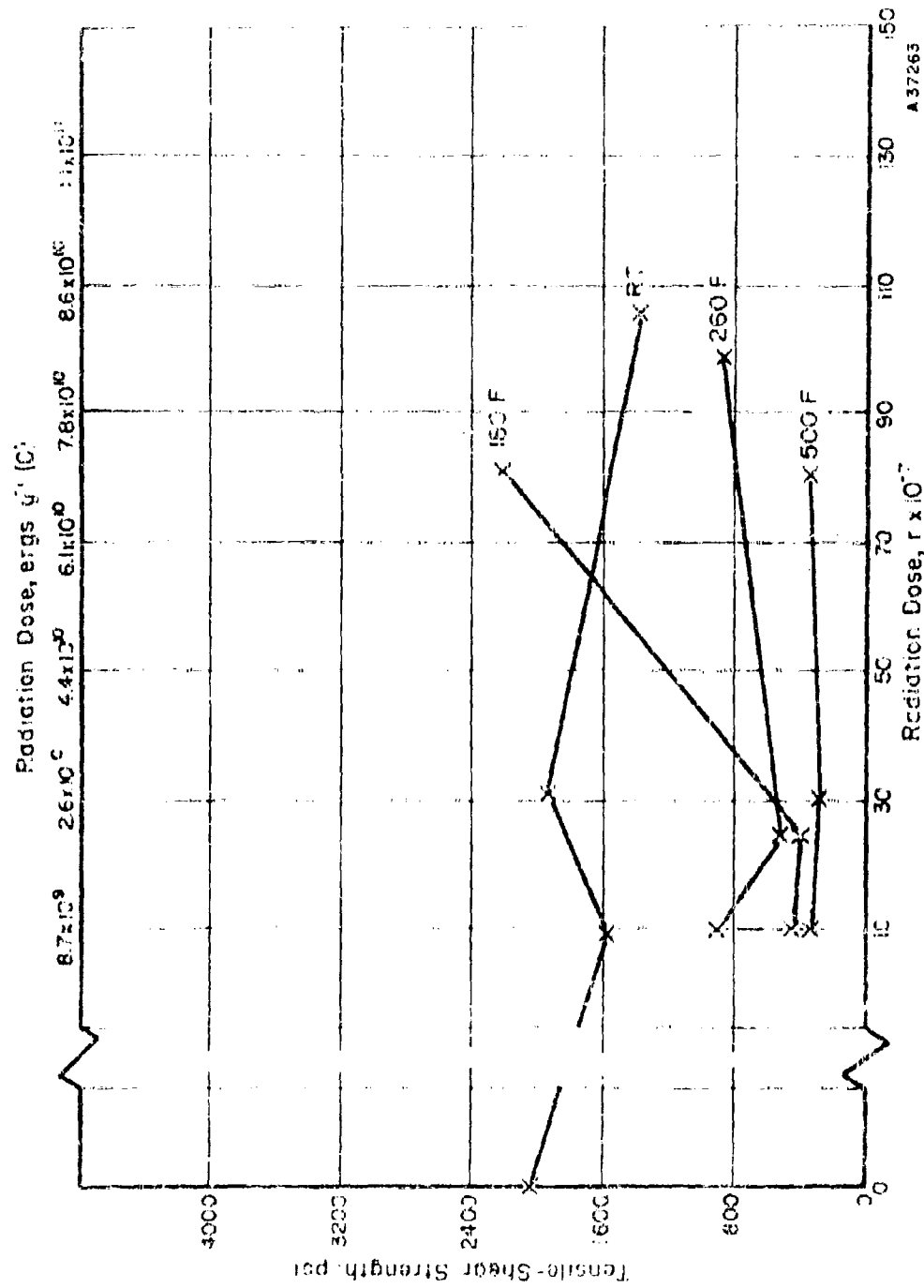


FIGURE B-21. EFFECT OF 75 F IRRADIATION ON TENSILE-SHEAR STRENGTH OF NITRILE RUBBER-PHENOLIC ADHESIVE CYCLEWELD A-Z TESTED AT 75, 180, AND 500 F (10)

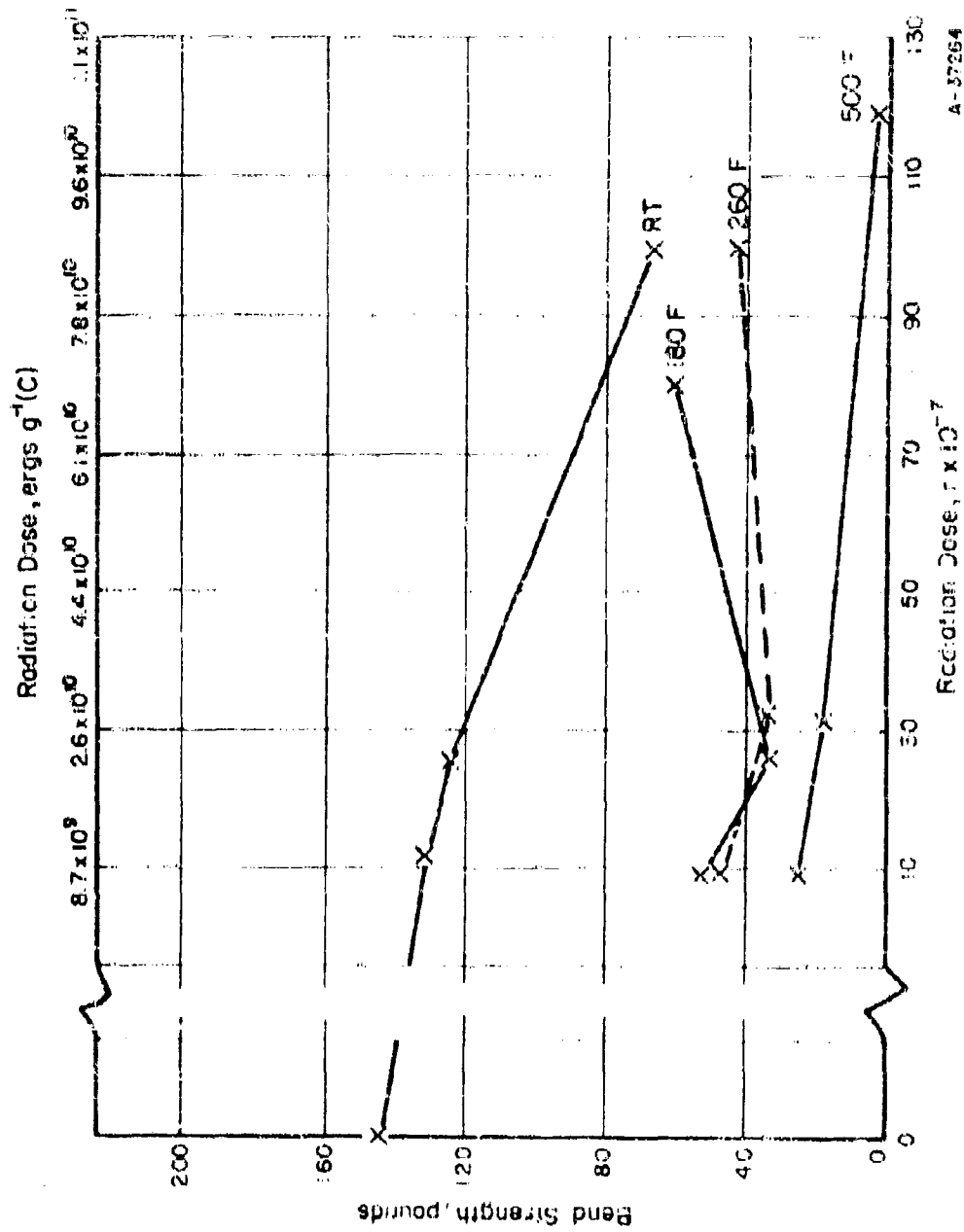


FIGURE B-22. EFFECT OF 75 F IRRADIATION ON BEND STRENGTH OF NITRILE RUBBER-PHENOLIC ADHESIVE CYCLEWELD A-7 TESTED AT 75, 180, 260, AND 500 F (10)

A-37254

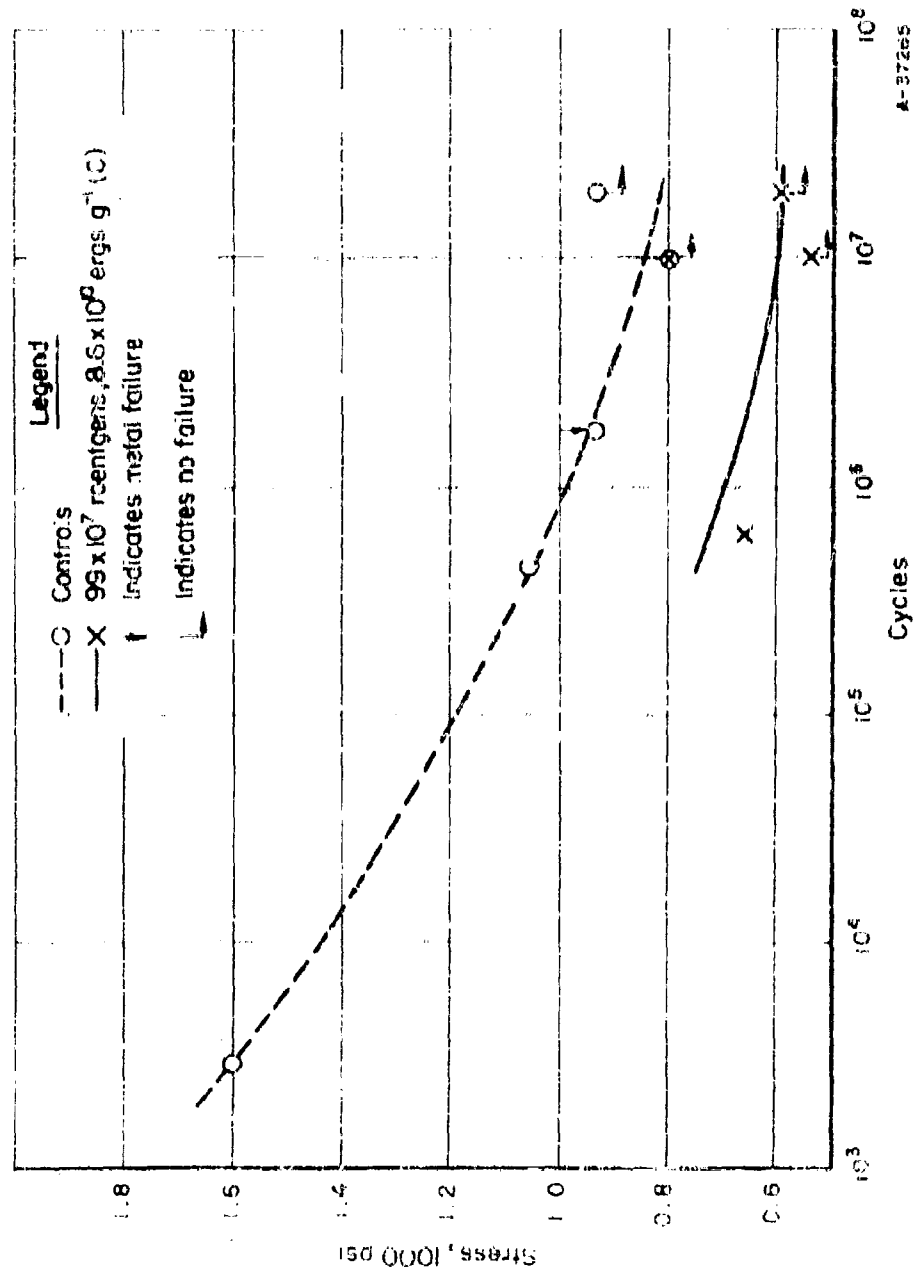


FIGURE B-23. EFFECT OF 75.5 kRAD IRRADIATION ON FATIGUE RESISTANCE OF NITRILE RUBBER-PHENOLIC ADHESIVE CYCLEWELD A-Z TESTED AT 15 PCF

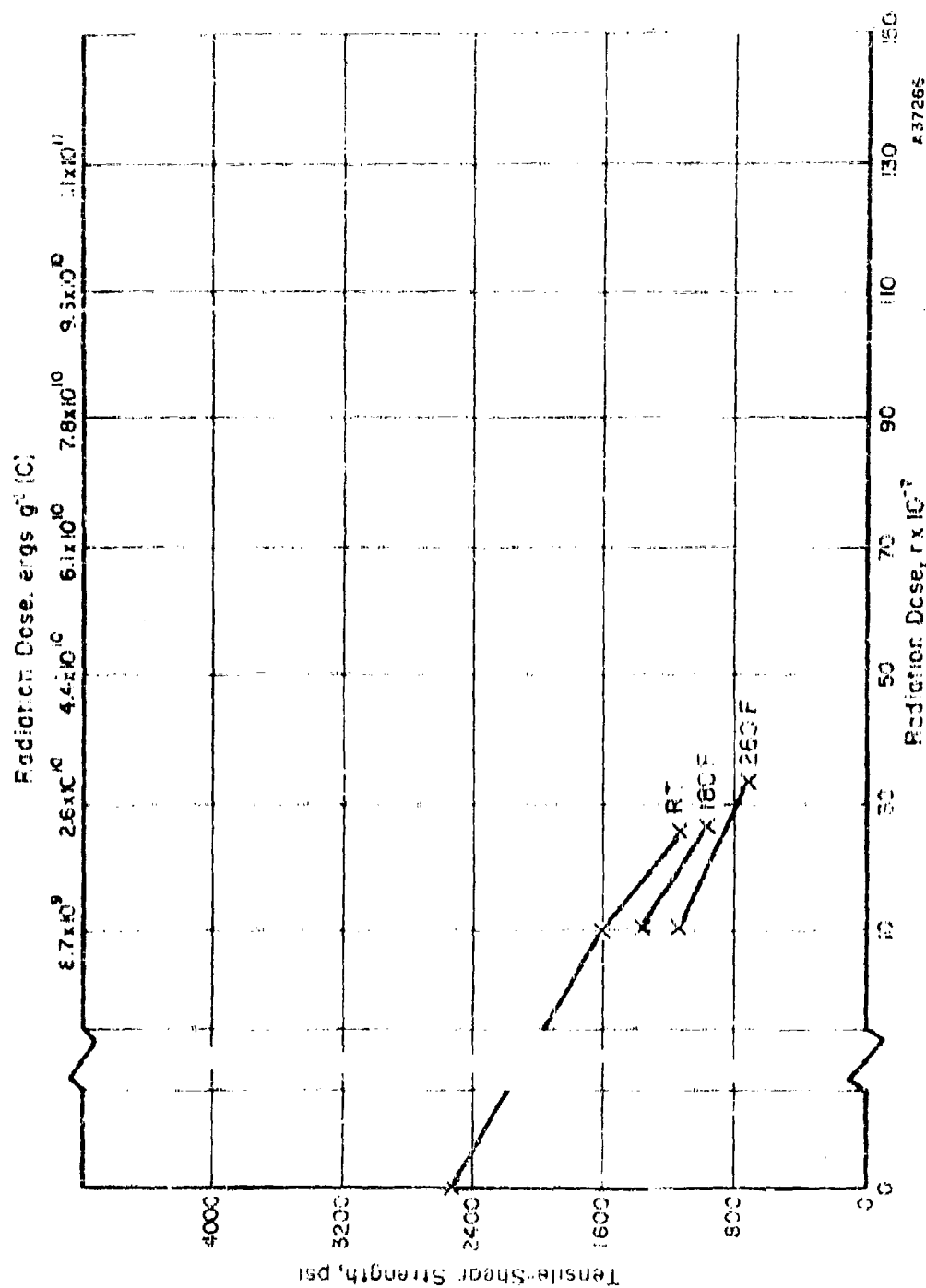


FIGURE 3-24. EFFECT OF 75 F IRRADIATION ON TENSILE-SHEAR STRENGTH OF NEOPRENE RUBBER-NYLON ADHESIVE CYCLEWELD C-3 TESTED AT 75, 180, AND 260 F (13)

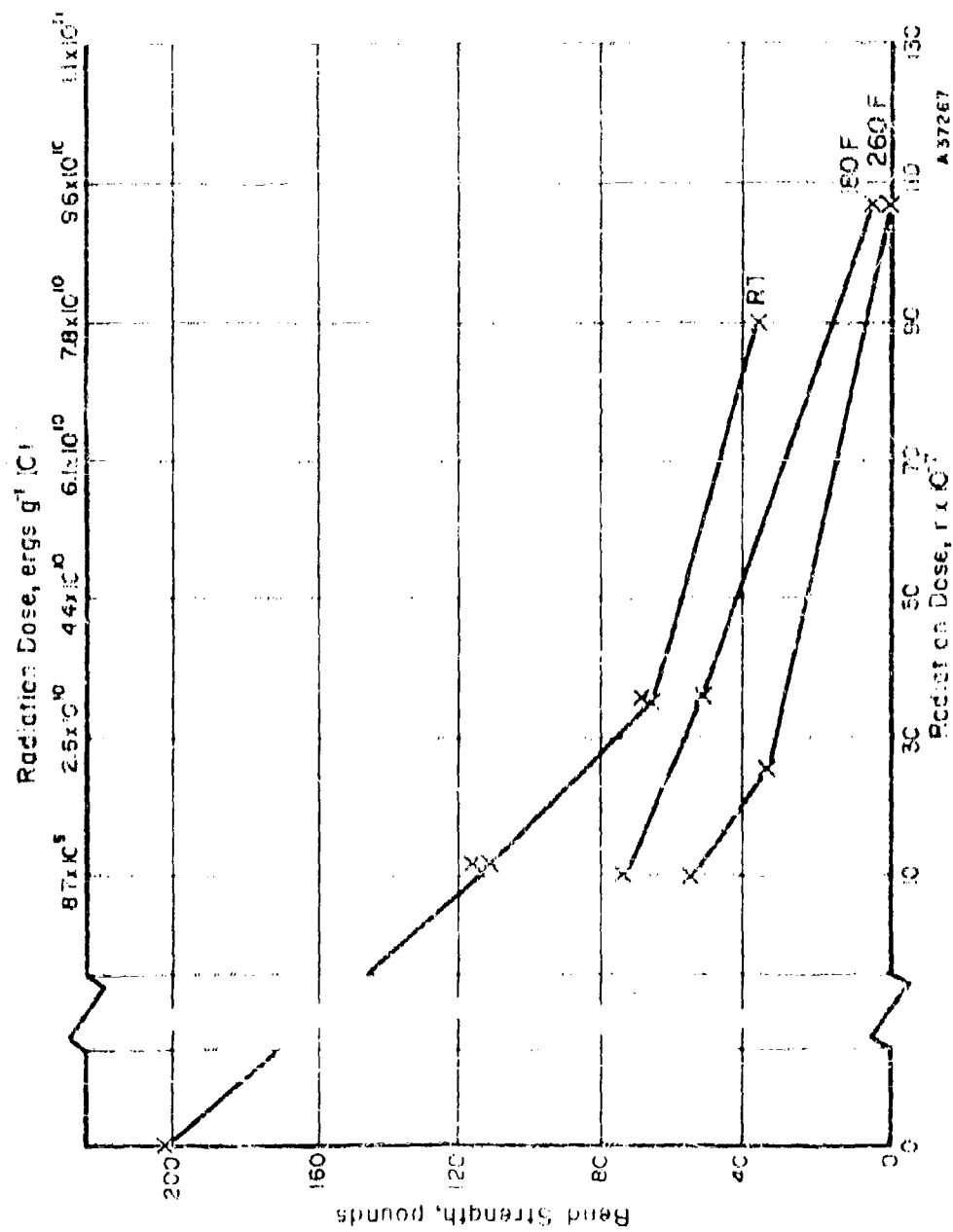


FIGURE B-15. EFFECT OF 75 F IRRADIATION ON BEND STRENGTH OF NEOPRENE RUBBER-NYLON ADHESIVE CYCLEWELD C-3 TESTED AT 75, 130, AND 260 F(10)

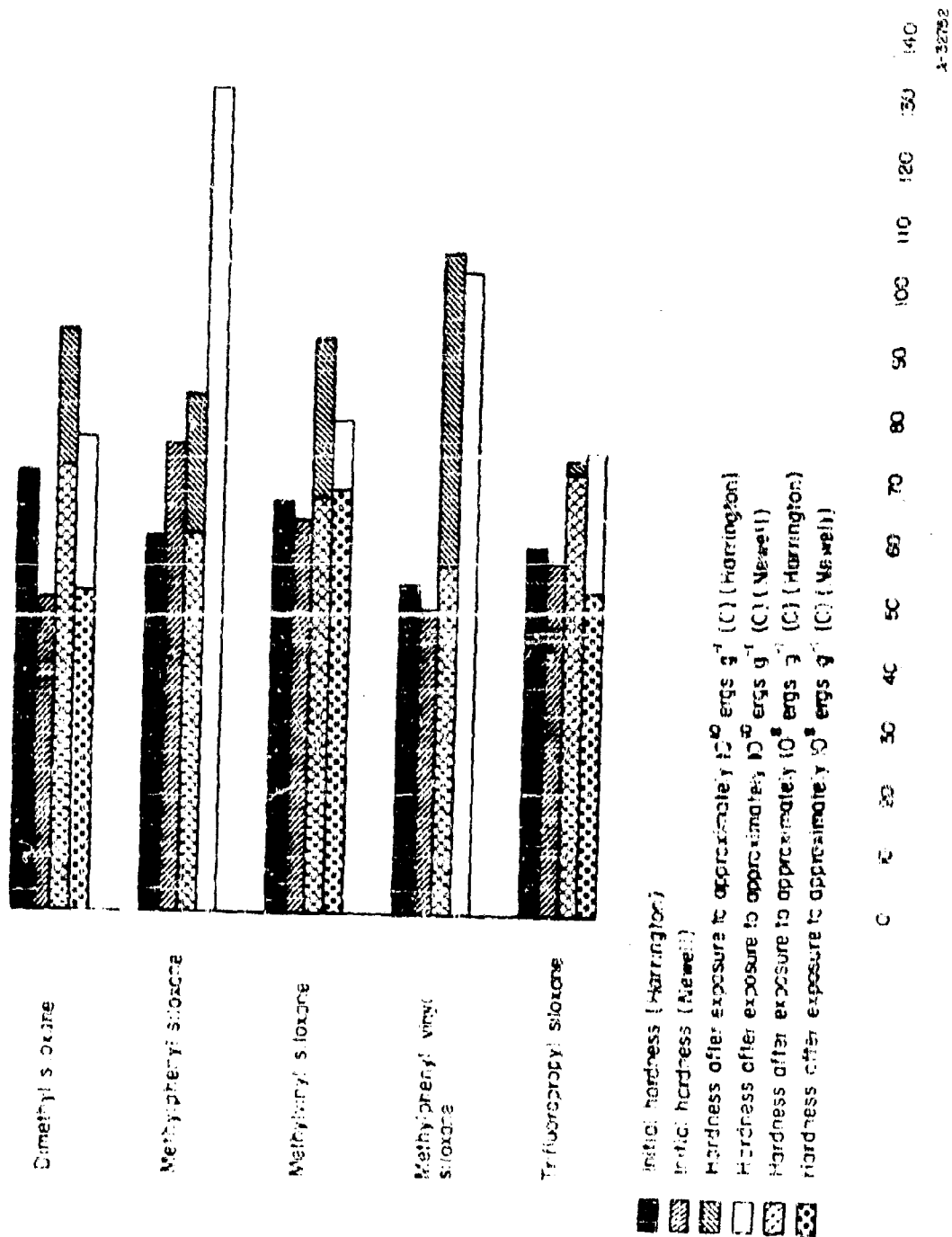


FIGURE B-26. COMPARISON OF INITIAL HARDNESS (SHORE A) WITH HARDNESS AFTER GAMMA IRRADIATION (100, 143)

X-32752

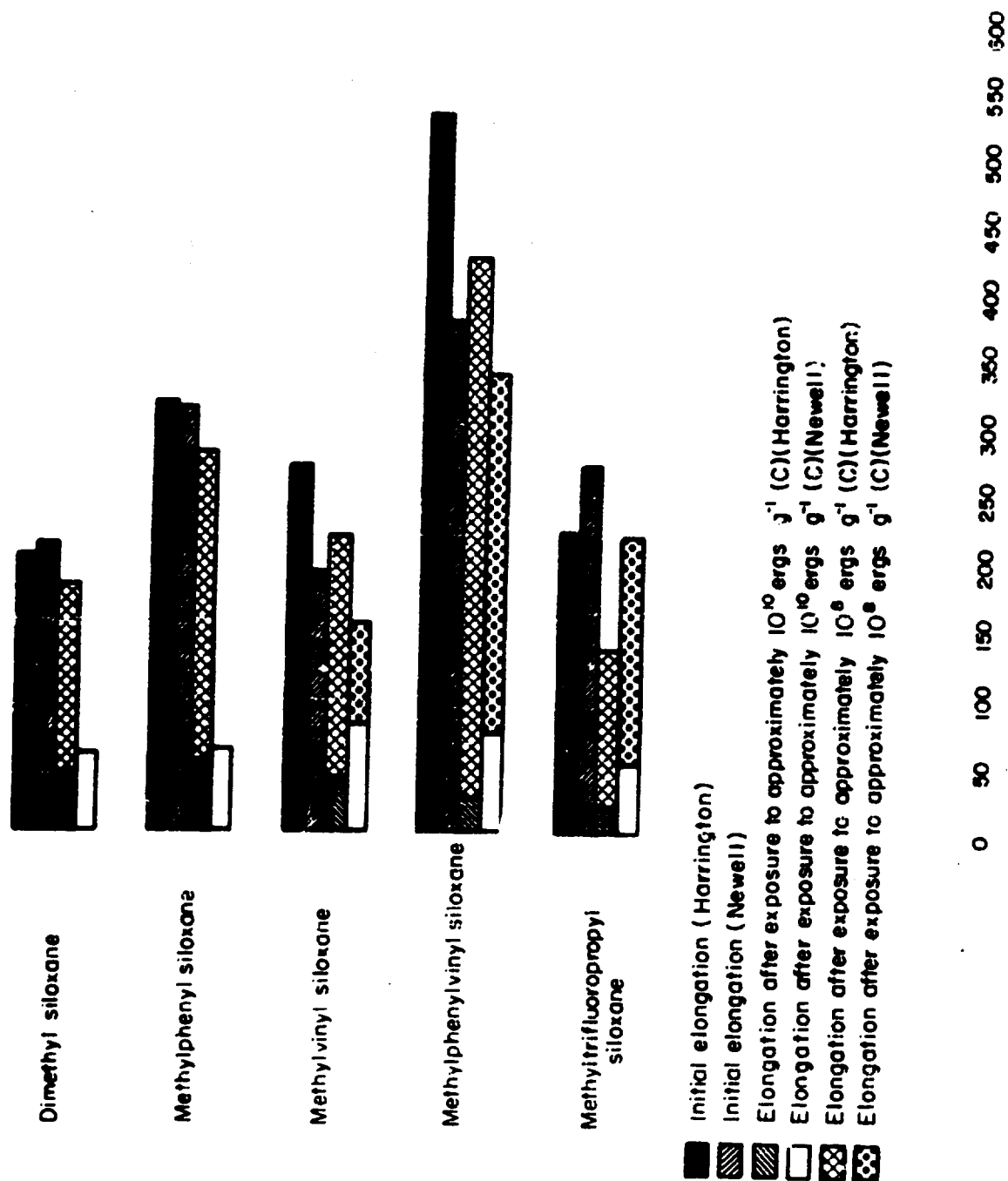
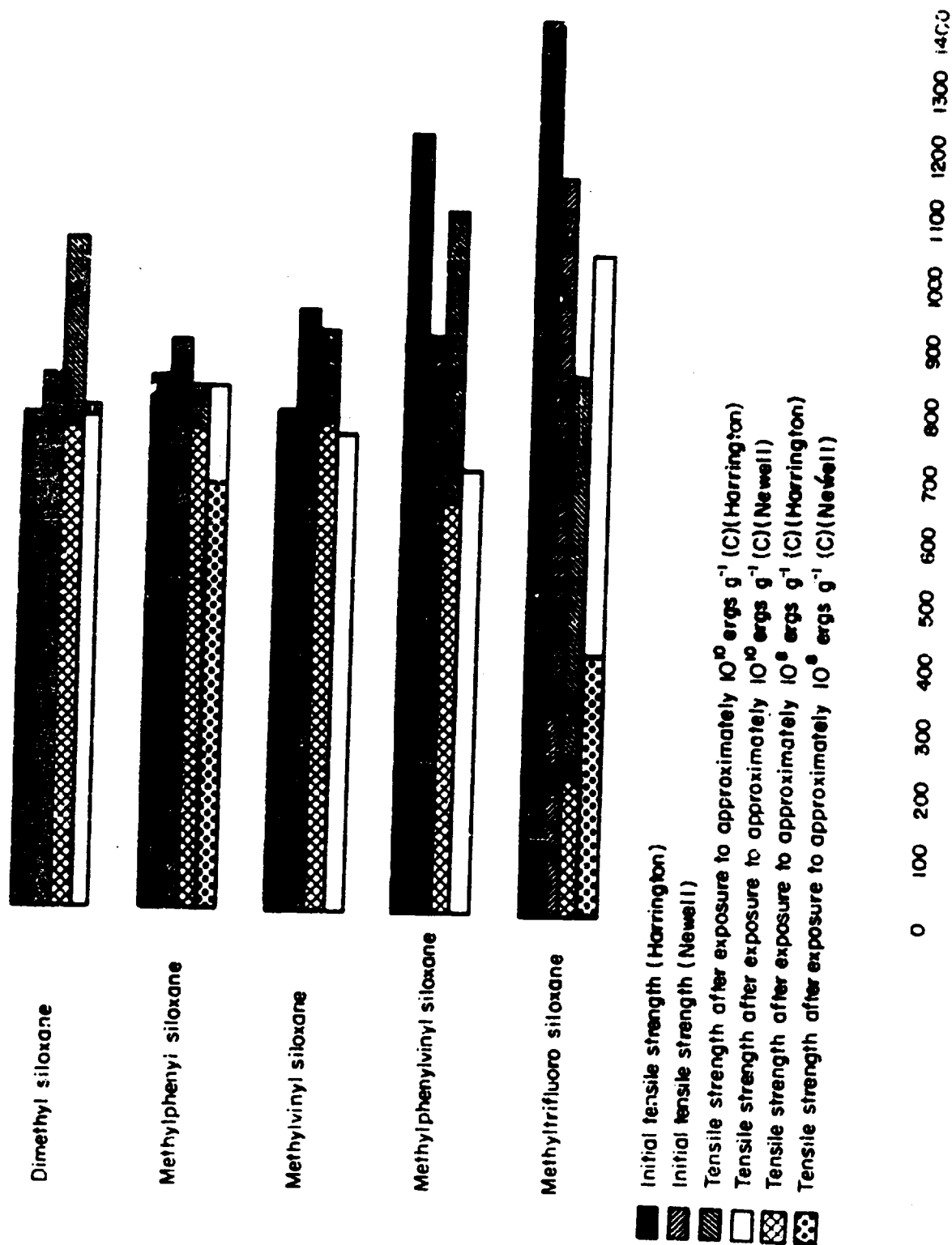


FIGURE B-27. COMPARISON OF INITIAL ELONGATION (PER CENT) WITH ELONGATION AFTER GAMMA IRRADIATION($10^5, 10^6, 10^8$)

A-32753



A-32734

FIGURE B-28. COMPARISON OF INITIAL TENSILE STRENGTH (PSI) WITH TENSILE STRENGTH AFTER GAMMA IRRADIATION(100,143)

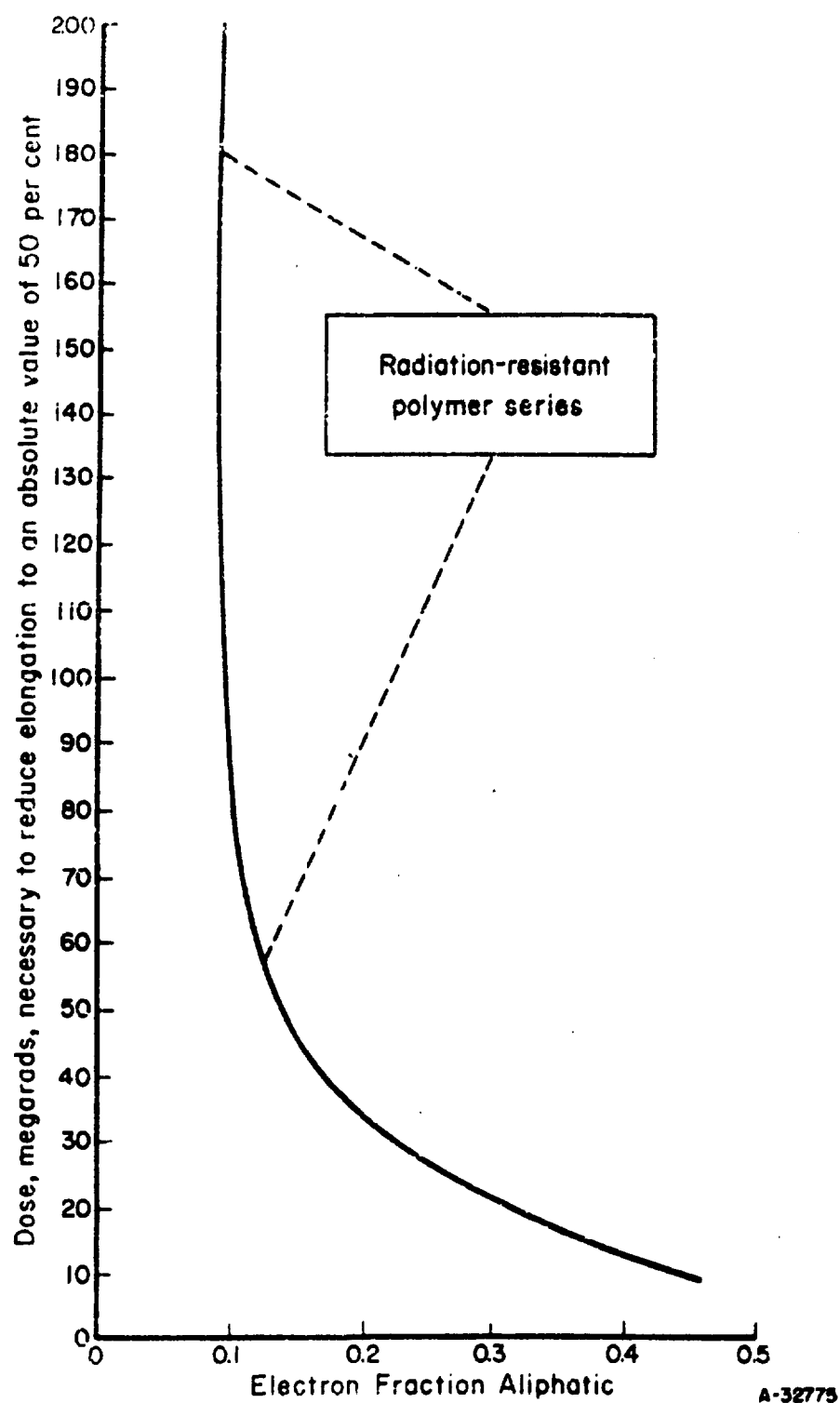


FIGURE B-29. SILOXANE POLYMERS IN THE SIMULTANEOUS ENVIRONMENT OF 200 C AND GAMMA RADIATION⁽¹⁴⁴⁾

Dose rate: 0.4 megarad per hour.

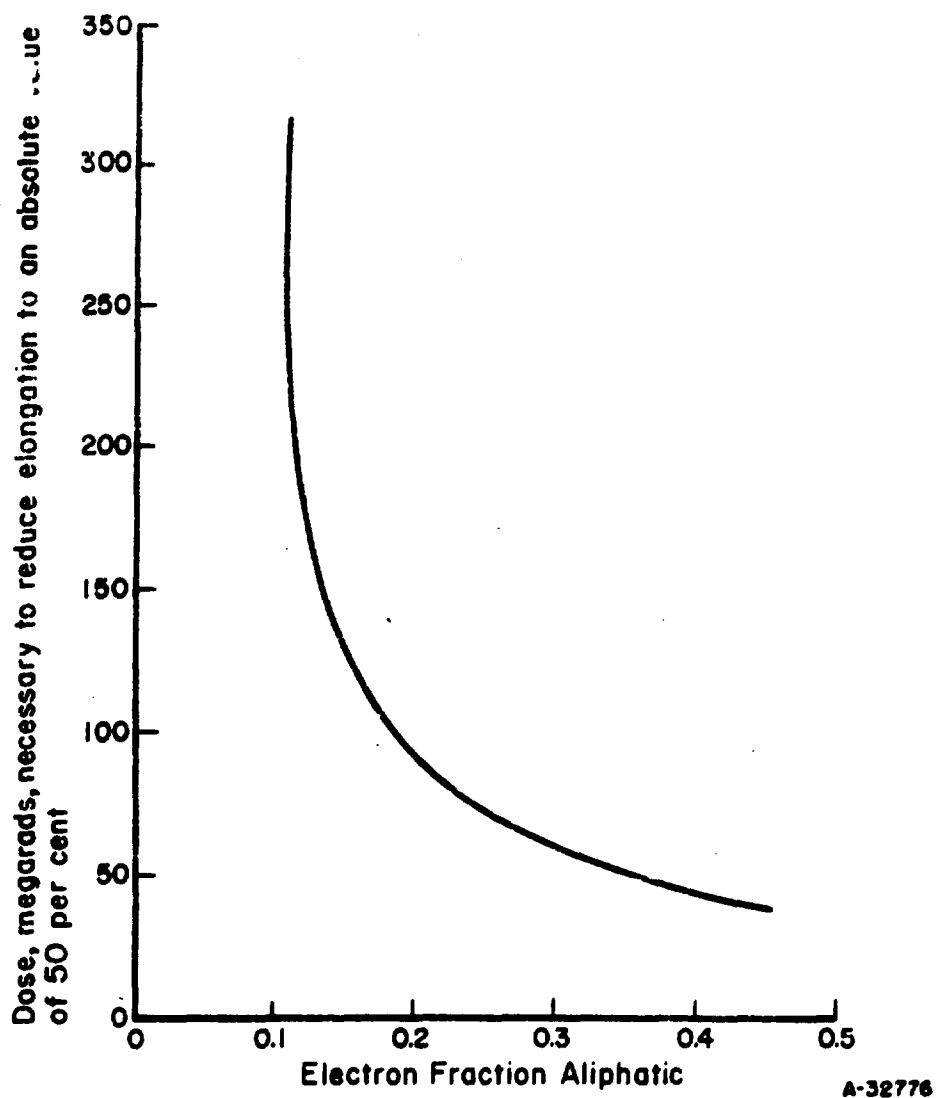


FIGURE B-30. SILOXANE POLYMERS IN AN ACCELERATED ELECTRON ENVIRONMENT⁽¹⁴⁴⁾

Estimated Temperature: 165 C.

APPENDIX C

RADIATION DAMAGE FIGURES FOR ELASTOMERS

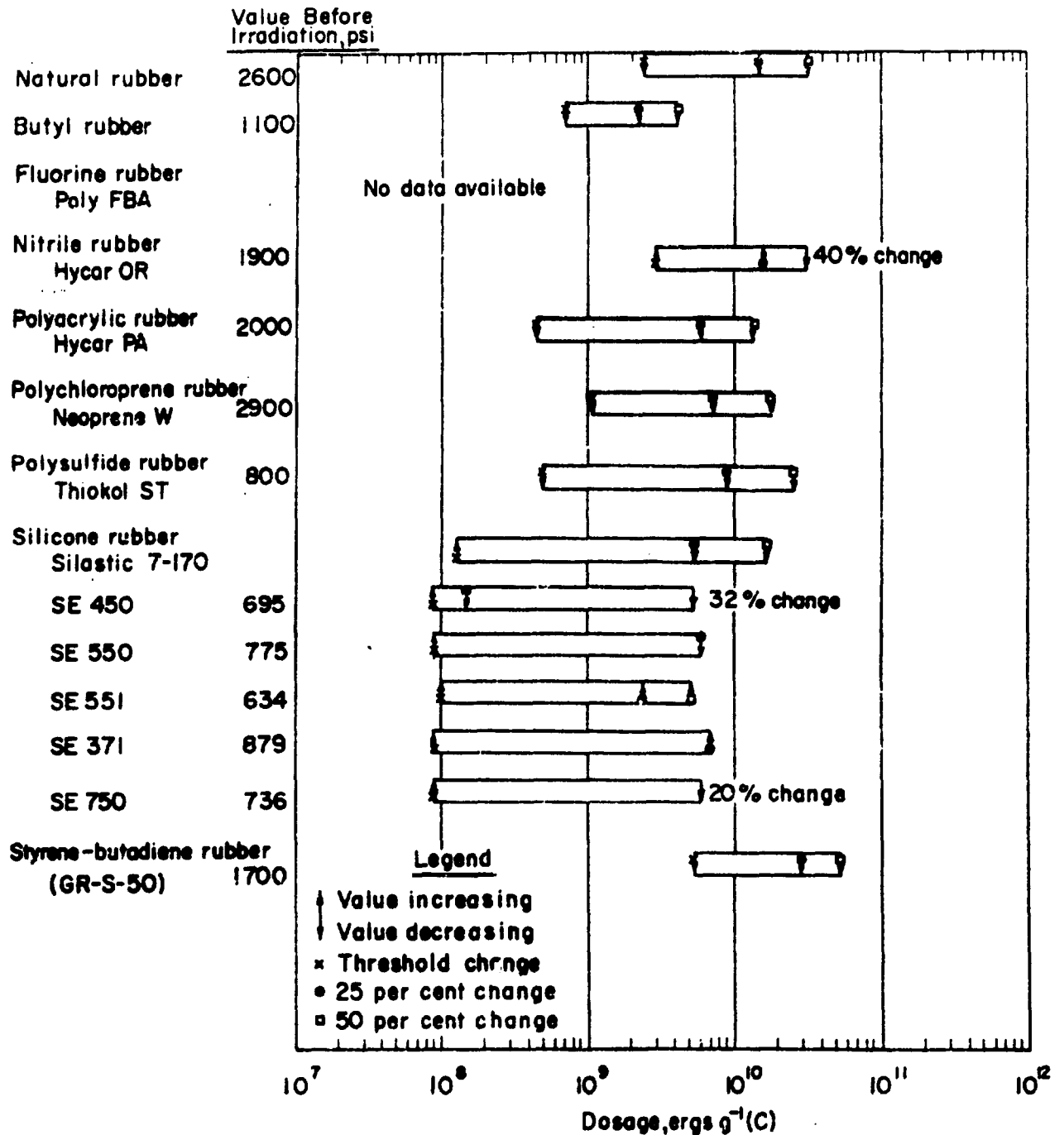


FIGURE C-1. RADIATION DOSE REQUIRED FOR THRESHOLD, 25 PER CENT, AND 50 PER CENT CHANGE IN TENSILE STRENGTH OF ELASTOMERS

Information source: ORNL-1373.

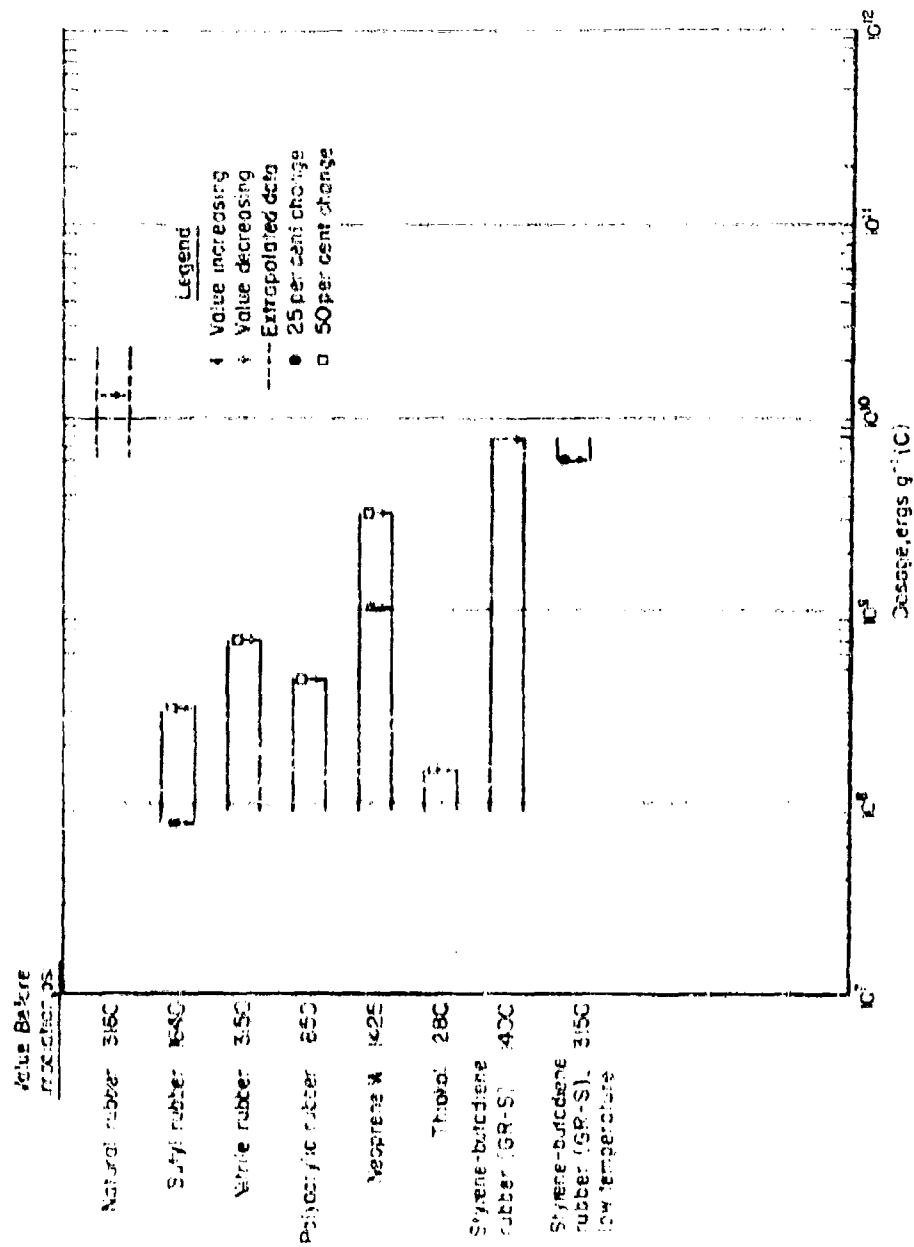


FIGURE C-1. RADIATION DOSE REQUIRED FOR 25 AND 50 PER CENT CHANGE IN TENSILE STRENGTH OF ELASTOMERS AS TESTED BY THE E. F. GOODRICH COMPANY

Information source: WADC TR 55-58, Part I

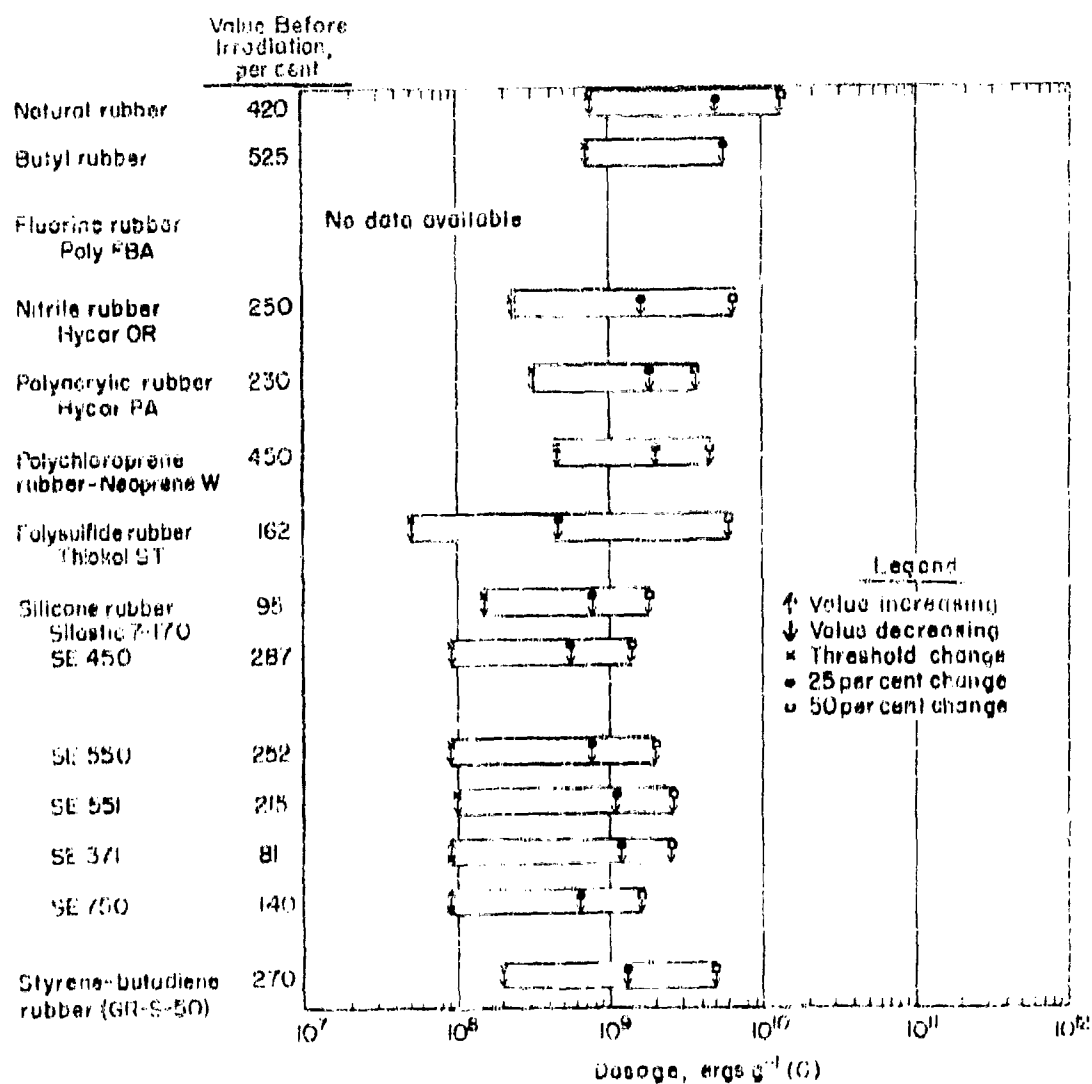


FIGURE C-3. RADIATION DOSE REQUIRED FOR THRESHOLD, 25 PER CENT, AND 50 PER CENT CHANGE IN ELONGATION OF ELASTOMERS

Information source: ORNL-1373

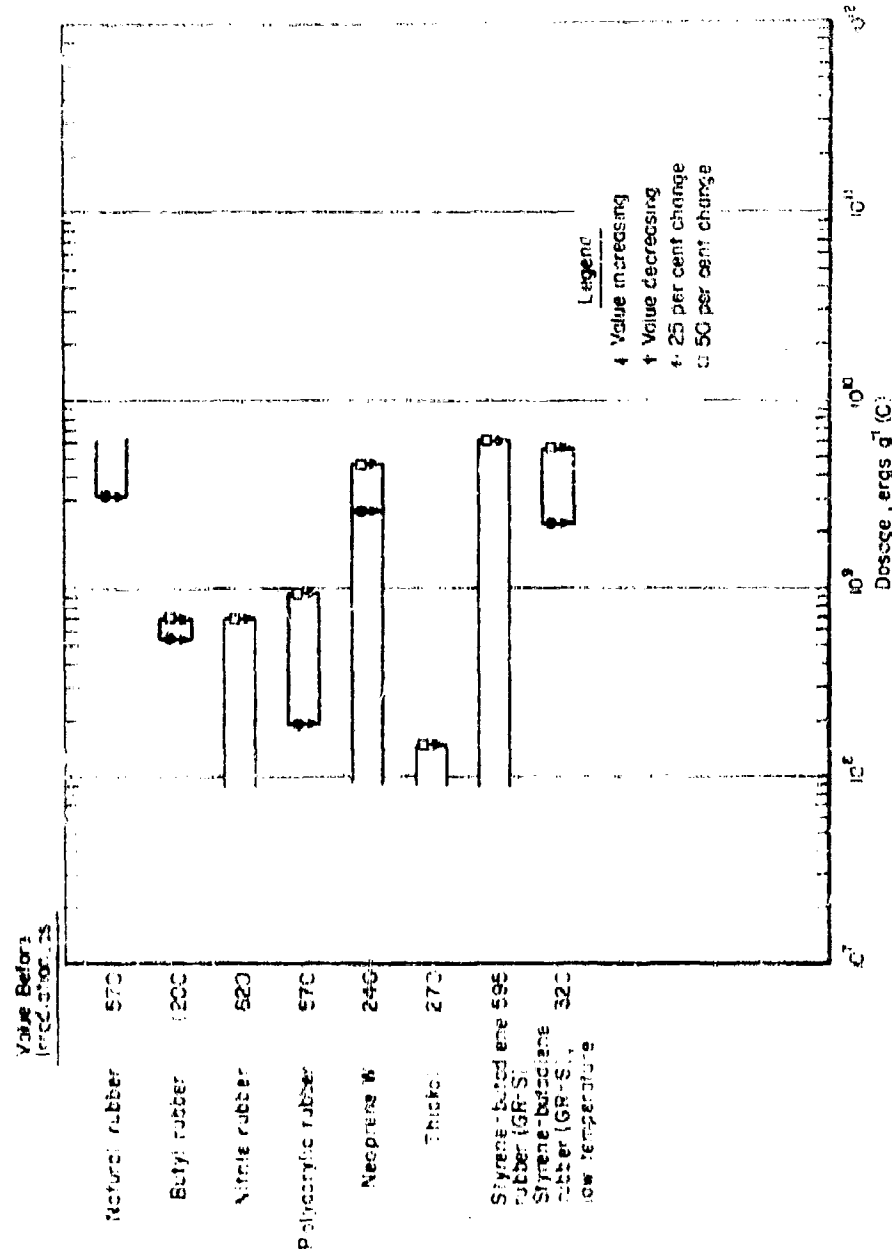


FIGURE C-4. RADIATION DOSE REQUIRED FOR 25 AND 50 PER CENT CHANGE IN ELONGATION OF ELASTOMERS AS TESTED BY THE B. F. GOODRICH COMPANY

Information source: WADC TR 55-58, Part I.

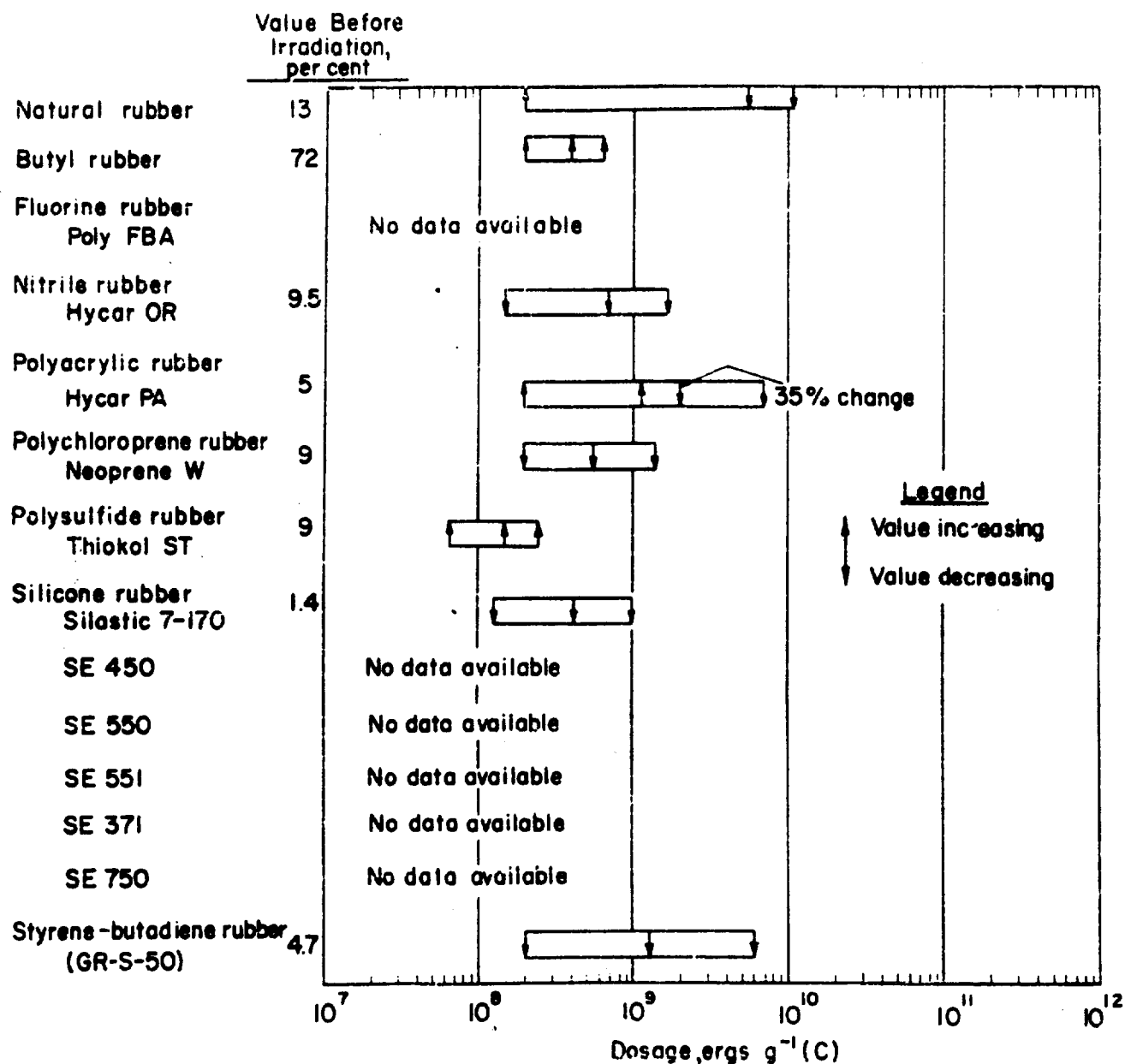


FIGURE C-5. RADIATION DOSE REQUIRED FOR THRESHOLD, 25 PER CENT, AND 50 PER CENT CHANGE IN COMPRESSION SET OF ELASTOMERS

Information source: ORNL-1373.

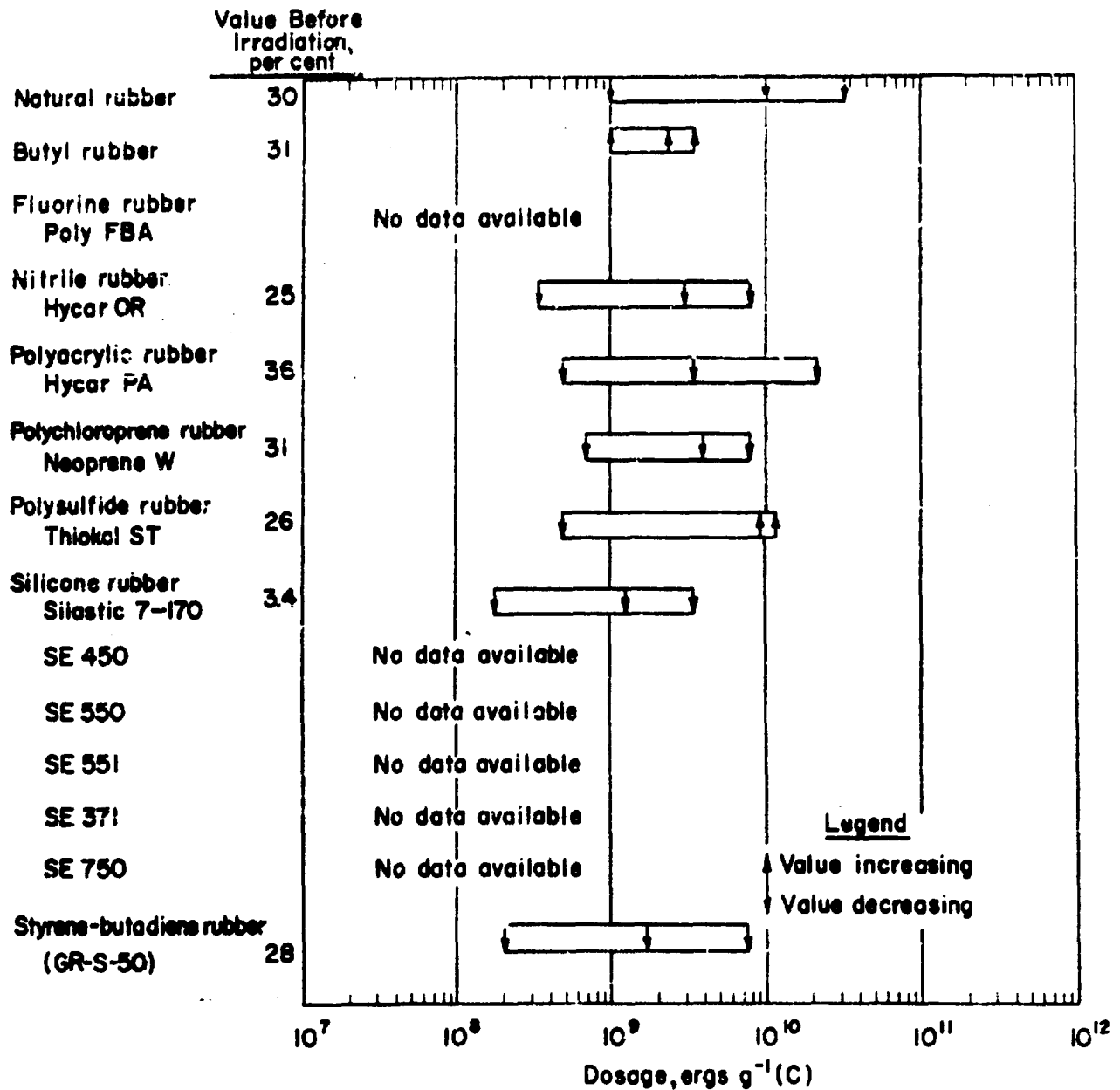


FIGURE C-6. RADIATION DOSE REQUIRED FOR THRESHOLD, 25 PER CENT, AND 50 PER CENT CHANGE IN STRAIN AT 400 POUNDS PER SQUARE INCH

Information source: ORNL-1373.

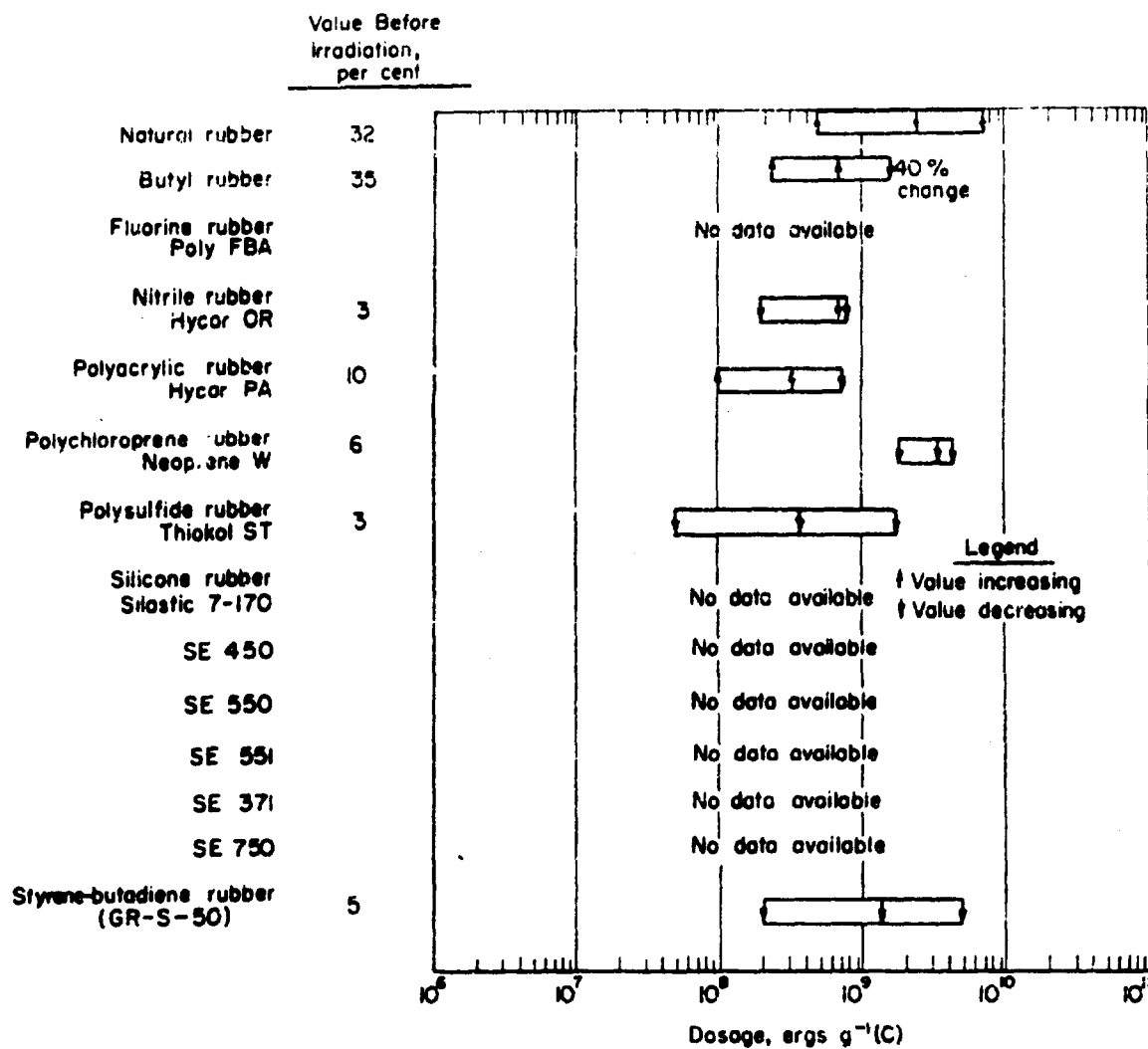


FIGURE C-7. RADIATION DOSES REQUIRED FOR THRESHOLD, 25 PER CENT, AND 50 PER CENT CHANGE IN SET AT BREAK OF ELASTOMERS

Information source: ORNL-1373.

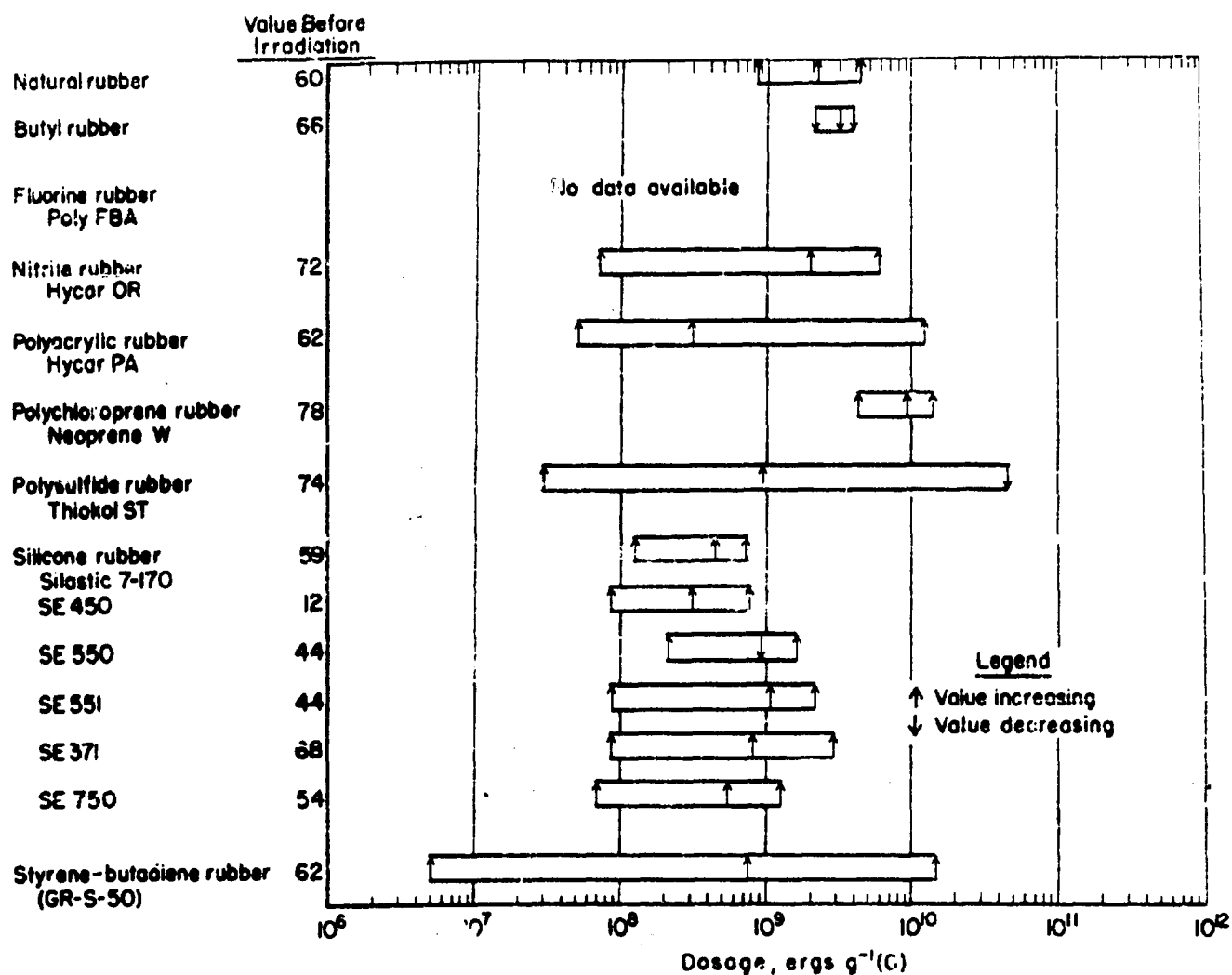


FIGURE C-8. RADIATION DOSES REQUIRED FOR THRESHOLD CHANGE AND CHANGES OF 5 AND 10 SHORE A HARDNESS UNITS FOR ELASTOMERS

Information source: ORNL-1373.

APPENDIX D

RADIATION DAMAGE FIGURES FOR PLASTICS

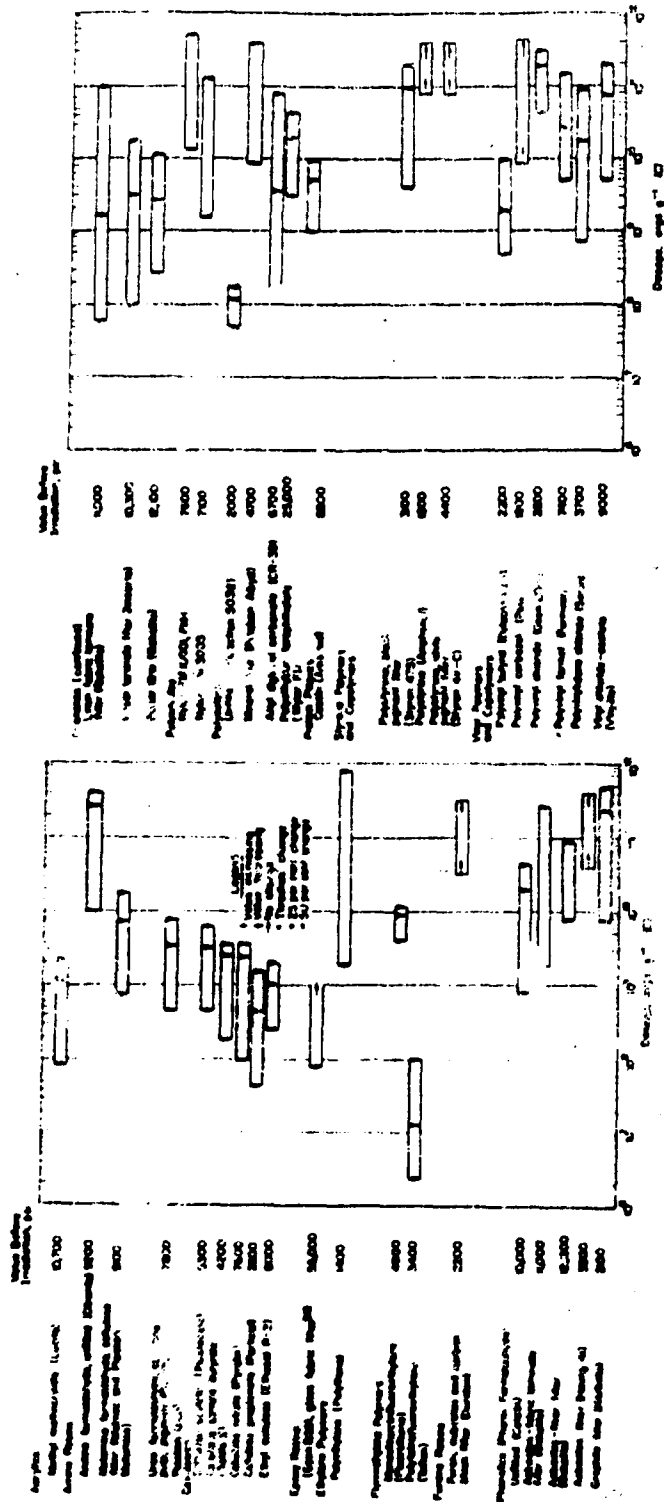


FIGURE D-1. RADIATION DOSE REQUIRED FOR THRESHOLD, 25 PER CENT, AND 50 PER CENT CHANGE IN TENSILE STRENGTH OF PLASTICS

Information sources: ORNL-928, and -1373.

FIGURE D-2. RADIATION DOSE REQUIRED FOR THRESHOLD, 25 PER CENT, AND 50 PER CENT CHANGE IN ELONGATION OF PLASTICS

Information sources: ORNL-928, and -1373.

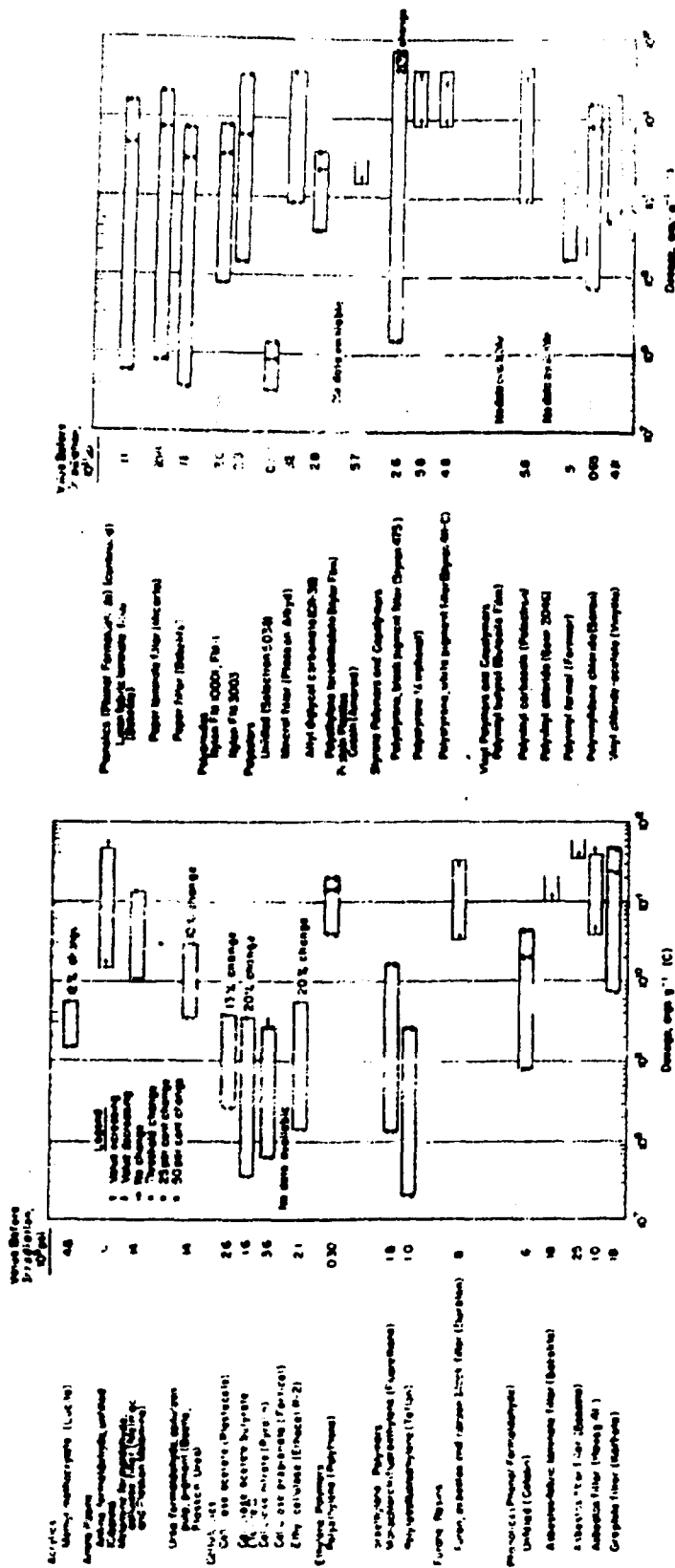


FIGURE D-3. RADIATION DOSE REQUIRED FOR THRESHOLD, 25 PER CENT, AND 50 PER CENT CHANGE IN ELASTIC MODULUS OF PLASTICS

Information sources: ORNL-928, and -1373.

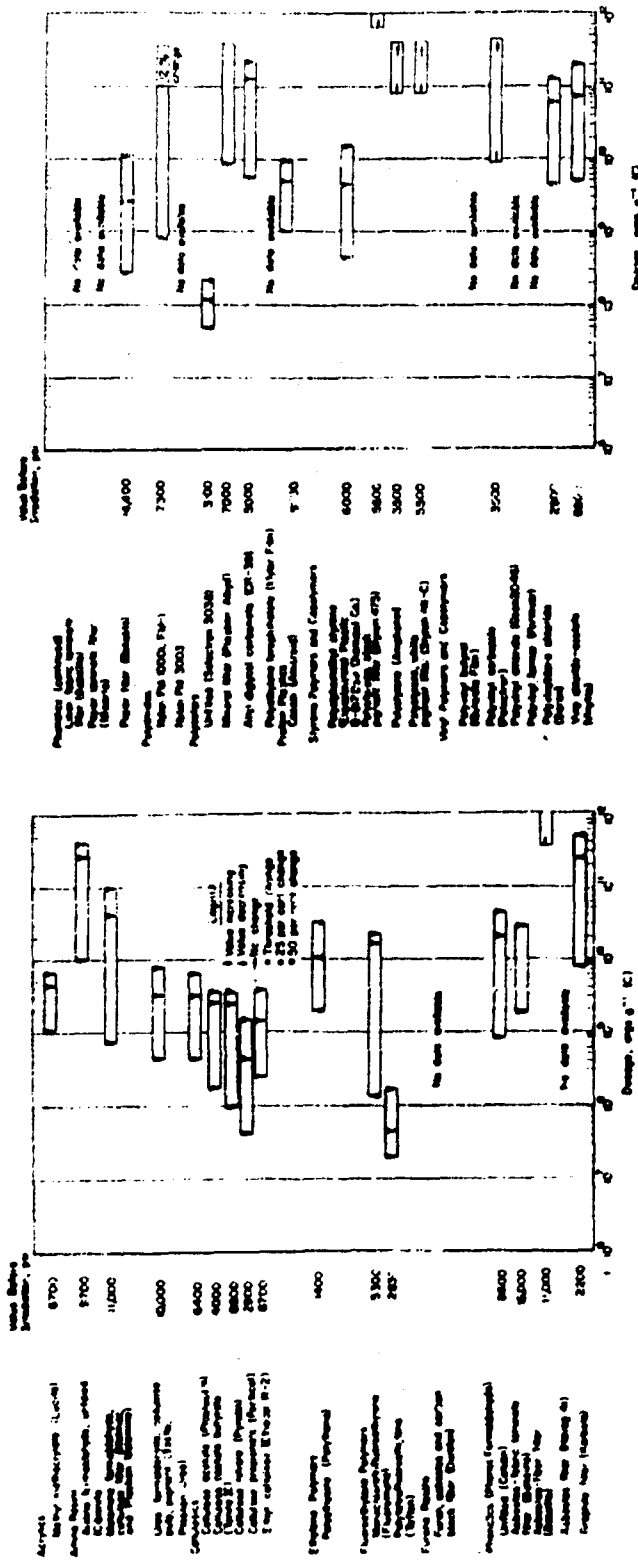
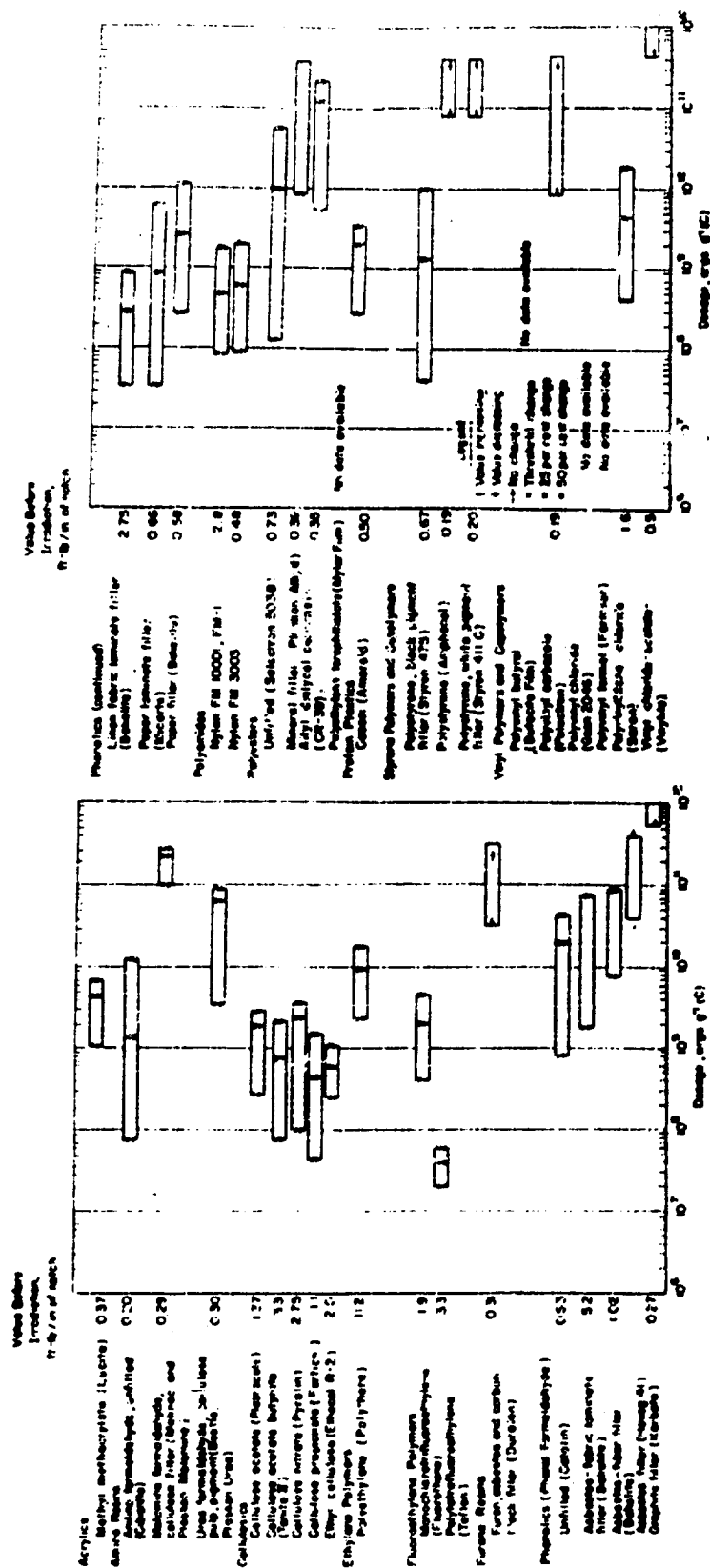


FIGURE D-4. RADIATION DOSE REQUIRED FOR THRESHOLD, 25 PER CENT, AND 50 PER CENT CHANGE IN SHEAR STRENGTH OF PLASTICS

Information source: ORNL-928, and -1373.

Information sources: ORNL-928, and -1373.



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